EXPERIMENTAL PAVILION.
Generating design, manufacturing and erection experience from full scale grid shell prototypes

A Master's Thesis submitted for the degree of
"Master of Engineering"

supervised by
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Affidavit

I, **ALEŠ VANĚK**, hereby declare

1. that I am the sole author of the present Master's Thesis, "EXPERIMENTAL PAVILION. GENERATING DESIGN, MANUFACTURING AND ERECTION EXPERIENCE FROM FULL SCALE GRID SHELL PROTOTYPES", 90 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 19.11.2015

Signature

Acknowledgements

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Abstract

The main goal of this Master thesis is to design and construct a grid shell structure, which is subsequently realized as an experimental structure on a prominent place in front of main entrance to Faculty of Civil Engineering (FCE), Czech Technical University (CTU) in Prague, Czech Republic.

There is a need for an elegant long-lasting structure which will at least partially cover an existing pool. This should make the place suitable for various events and also a friendly, pleasant, relaxing and free time space. By thinking about how such structure should look like and what materials and structure types are suitable, there were many kinds of lightweight structures considered. The direction which the CTU is focusing on nowadays is to experiment new and original possibilities of building structures, create sustainable architecture and consult with other specialized departments on FCE CTU on higher level during the design process.

Single layer tensioned membrane structures are at present very popular, however, finances could be an obstacle. Tensioned membrane structures would require cable anchoring, which is not suitable to anchor around the pool where walkways are located. For these reasons, the most logical solution is to create a grid shell structure combining with a single layer membrane that would fulfil all aspects of elegant remarkable lightweight structure using some original details and workflow advancements. The goal of this project is to design a structure which will then be built in spring 2016 in cooperation with other departments and students from FCE CTU Prague.

This grid shell project should demonstrate another possibility to build and think about unconventional structures and provoke a deeper interest in these unique structures. In the Czech Republic such systems have not been applied in an adequate scale as a permanent structure yet.

The goal of this Master thesis was to create a feasible design of a grid shell structure and to build up this structure while being capable to understand the core of this interesting phenomenon. As a starting point there was a first workshop organized in cooperation with students and friends, many different materials were used for physical modeling and the very first mesh was assembled.

This master thesis documents an experimental pavilion design procedure from the starting design point to a complete built structure and reports on the experiences and knowledge gained. The work describes a step by step workflow of procedures with author´s comments, bibliography references and pictorial documentation.

Contents

1 Introduction

This thesis documents the project that provides partial covering of a pool in front of the main entrance of Faculty of Civil Engineering CTU in Prague, Czech Republic.

At present there is no specified function for this place, the pool is mainly used by students as a free time picnic and relaxation place between classes. After revitalization with new facades on Buildings A and C in 2014, there is vicinity modification with new grass surface. The pool which has a few wooden plates for sitting has not been changed. There is no discussion on what to do with such an outdoor „sculpture“, which is a reminder of previous communist ruling.

The goal is to dulcify this exposed and significant place to create a cozy place for pleasant relaxation. This place could have also the function of background for various events and should fulfill a function of an interesting college sign.

The design is about creating a partial cover structure, which would be able to make the area more pleasant. First a single-layer tensile membrane was considered, but later changed for a covered grid shell structure. Single-layer tensile membrane needs a primary structure system. In most cases, the system would require steel and cable components, which would not have been suitable for this area because of visual impact and less space. A grid shell does not need the above mentioned. It is a shell structure which stands clearly and clean, may in combination with a translucent membrane cover. The goal is to give an impression of lightness and elegance, aesthetics and originality. In addition to these advantages, the grid shell CTU project can be built entirely in cooperation with the help of students during a workshop.

The designed cover must also fulfill the need of protection against rain and solar radiation, because the area is south oriented. Potential membrane cladding technologies are processing in authors dissertation.

The orientation is welcomed for sufficient amount of daylight and guaranties enough light, especially during sunny days offers a cozy space at the end of the Thákurova street axis.

Adjacent to the site, there is the National Library of Technology which was built in 2009, as well as the new Faculty of Architecture that was built in 2010. These buildings are significance to the project site. Before both buildings were built, this area was used as a parking lot for students and Faculty employees. At present this area is a nice public space which many students frequently occupy.

Lightweight architecture in general belongs to a field of designing, where a lot of new things could be discovered and pushed forwards. New building technologies, sustainable materials and complex detailing are a few examples.

The aim is to realize a sustainable project, which is something that keeps all Lightweight designers motivated to reach the best result. This Master thesis deals with using thin timber laths to demonstrate the potential of such structures. The field of lightweight structures is a wide topic, this Thesis is focused just on a part of it, trying to find an adequate solution for a relaxing pavilion.

Shigeru Ban:

„Shell structures are but one of many different, interesting structural systems. If a grid shell structure happens to be suitable for a project, I use it, but otherwise I design another appropriate system. An architect shouldn´t concentrate on one type of structure, and should take notice of all possible structural systems. Without an understanding of structures, we cannot design a building. If you would have some preferences, it would be very difficult to adjust to different programs.“ [1]

2 Terms and history of Grid shell structures

This chapter offers a closer look at lightweight grid shell structures including definitions and descriptions of the basics, citations, historical examples, advantages and disadvantages and pictorial documentation.

2.1 Definition of Shell structures and Grid shells

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.

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.
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.* [2]

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.* [3]

“Grid shell structures do have an interesting history. The name "grid shell," particularly in Europe, became a way to describe free form combinations of dome-type curvature and inverse curvature in a single lattice. But, at first, grid shells had either positive curvature, as geodesic domes, or negative curvature as hyperboloids.”

In the closing decade of the 19th century, Russian engineer Vladimir Shukhov built tall towers with criss-crossing straight line generators that formed hyperboloids of revolution. In the late 1920s, Walther Bauersfeld created the first geodesic dome as formwork for a planetarium in Germany, and subsequently, Buckminster Fuller started popularizing this form in the 1950´s.” [4]

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

Fig. 2.1 Pantheon, Roma [by author 27.7.2013]

The Pantheon (on Fig. 2.1) 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 Figure 2.2 a concrete shell covers the natural theatre in Grötzingen near Stuttgart.

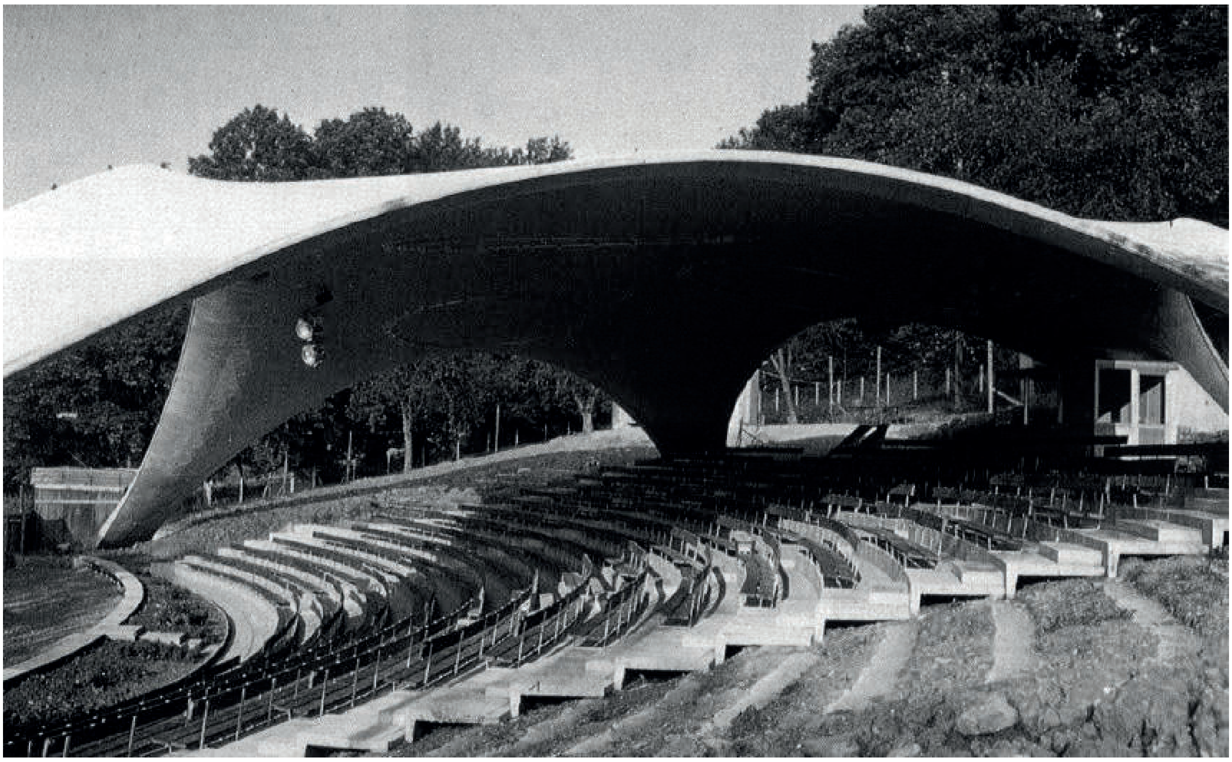

Fig. 2.2 Concrete shell made by Heinz Isler [5]

2.2 Forerunners of grid shells

This chapter introduces two main examples of grid shell evolution. 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." [6]

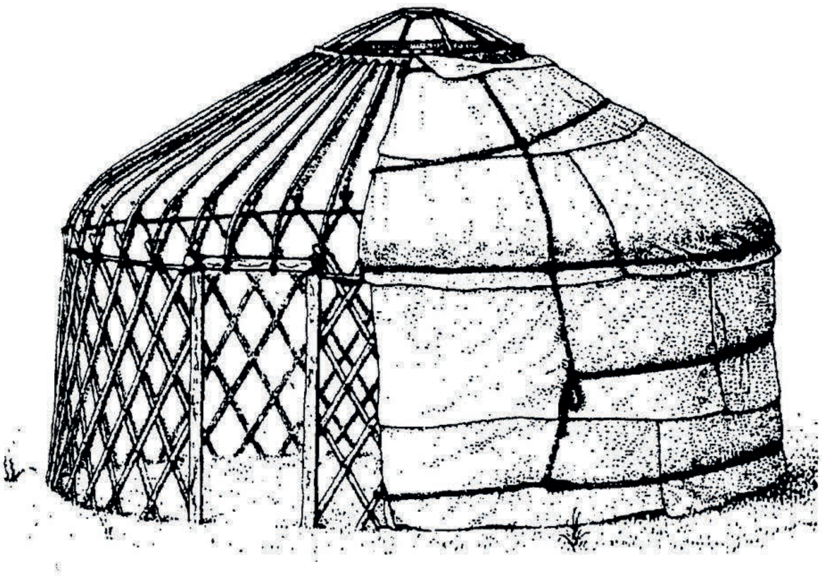

Fig. 2.3 Mongolian Yurt – structural solution – design sketch [7]

Fig. 2.4 Mongolian Yurt – structural solution – realization [8]

As an example of a modern Grid shell one must mention Buckminster Fuller, who was the pioneer of grid shell structures. 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.” [9]

Fig. 2.5 Richard Buckminster Fuller´s Geodesic dome structure [10]

Fig. 2.6 Richard Buckminster Fuller´s Geodesic dome structure [10]

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 so useful for many other activities, and could result in wasted land or space.

2.3 Advantages (and disadvantages) for using grid shells

Advantages of using Grid shells in architecture may include: sustainable use of material such as timber, self forming process of the complex curved geometry during erection from an initially flat configuration. These attributes makes grid shells economic both in minimal use of material and manufacturing costs, as such they may be considered sustainable. On the other side, the necessity of well done form-finding, the dependence on particular material properties and complex procedures during the erection and finally their low stiffness have kept grid shells in a niche compared to other modern shell structures.

2.4 Form finding techniques

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.

2.4.1 Physical form-finding

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. 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.

- For this purpose, from practical point of view, three different physical technologies of modeling procedures may be used:

I. Erecting a grid with hinged connections by pushing the edges inside the grid. Stripes of hard plastic may be used for such models. The model in Figure 2.7 is made of HIPS (High Impact Polystyrene) and connections with a rotation joints Another suitable testing material is a plastic net, used often in gardens to protect trees and bushes from the animals. This grid has no scale, it is just a playful material for the first form finding steps.

    HIPS is a low cost plastic material that is easy to machine and fabricate. HPS is often specified for low strength structural applications when impact resistance, machinability and low cost are required. It is frequently used machining pre-production prototypes since it has excellent dimensional stability and is easy to fabricate, paint and glue. [11]

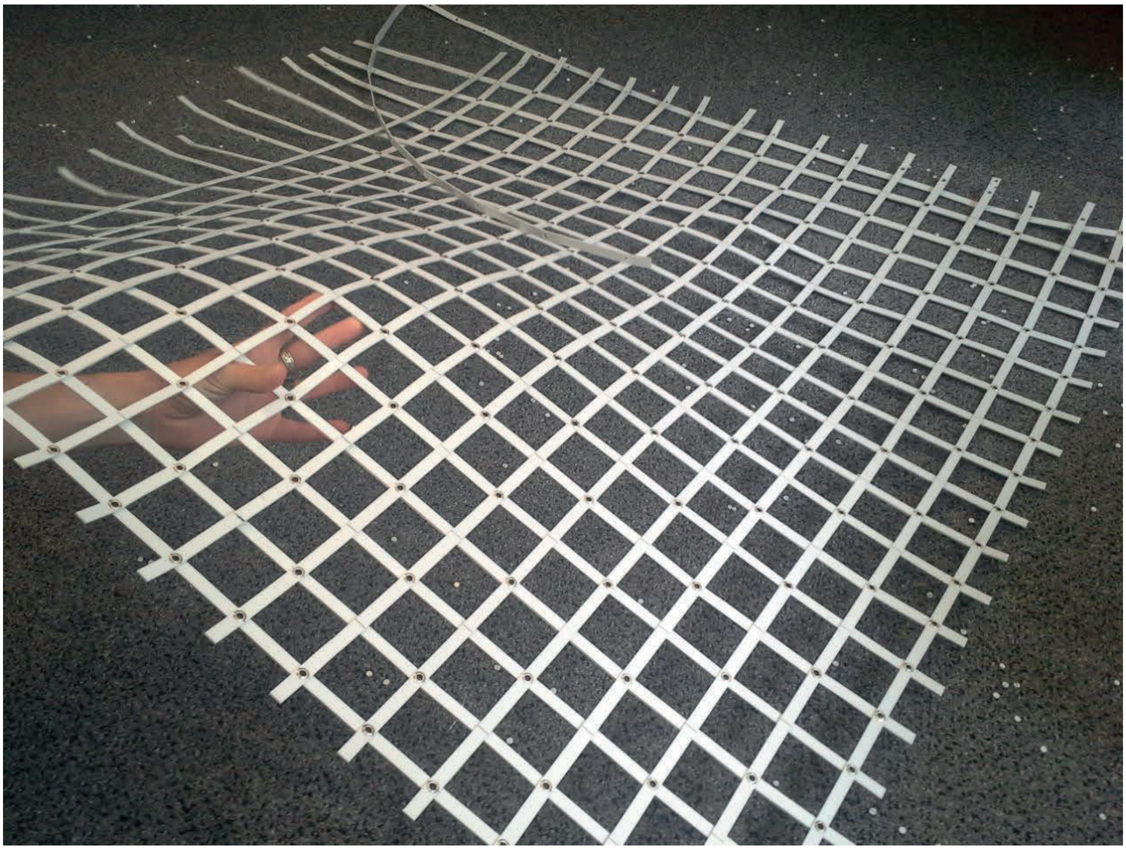

Fig. 2.7 Grid made from HIPS stripes [by author]

An excellent material which was brought to light during this Master thesis, is a white wall-reinforcing grid with measure 1:100 (when considering the grid in reality has dimensions of 0,5 x 0,5 meters). The grid dimension 0,5 x 0,5 m was first done from practical point of view in agreement with human scale, at the time Frei Otto built his cable structures. Such a grid is safe (prevention of fall threw) and one is able to climb and walk on it quite easily.

The advantage is possibility to change the grid geometry easily, especially to change the angle in the grid by pulling the grid in corners (Figure 2.8 above).

It is not possible to make a design with high degree of double curvature. In case of grid shells it is possible to learn a lot from small scale models, yet using bigger models would of course add better sense to the structural scale.

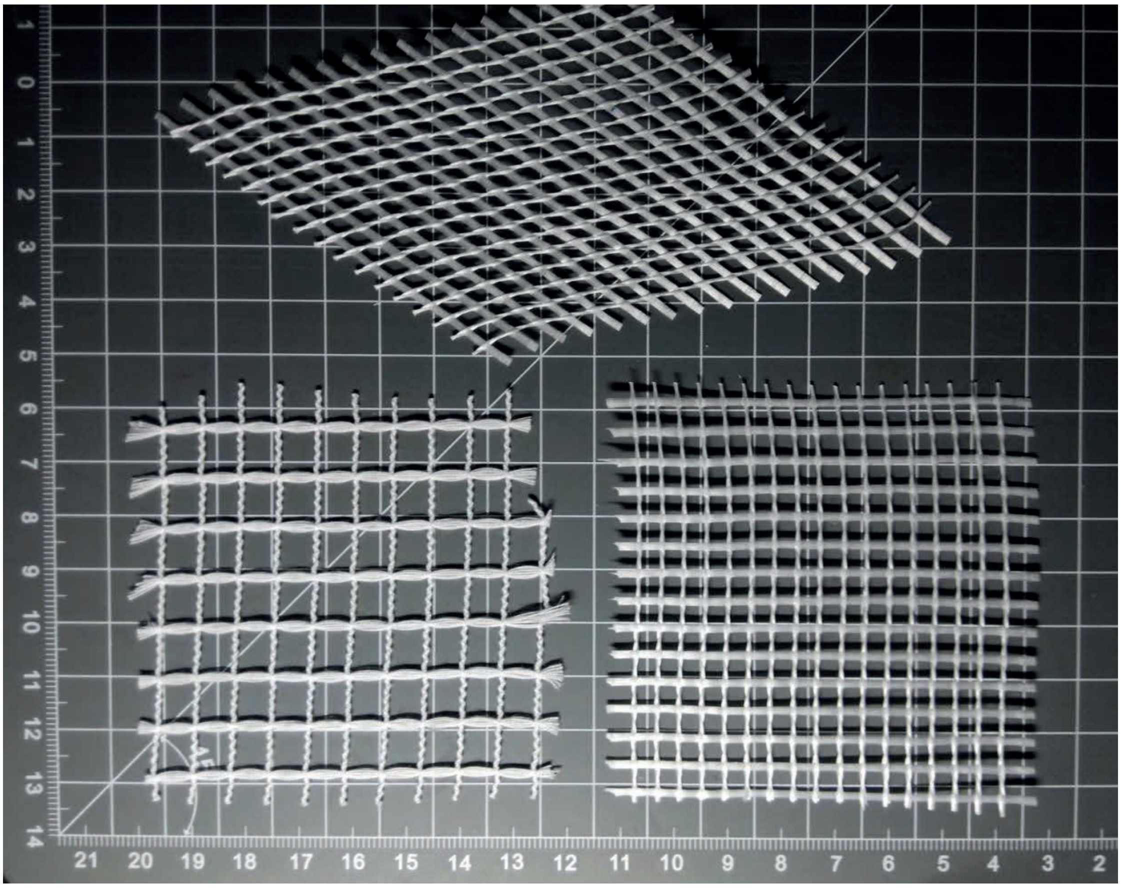

Fig. 2.8 Material for physical modelling, suitable for method I. [by author 13.9.2015]

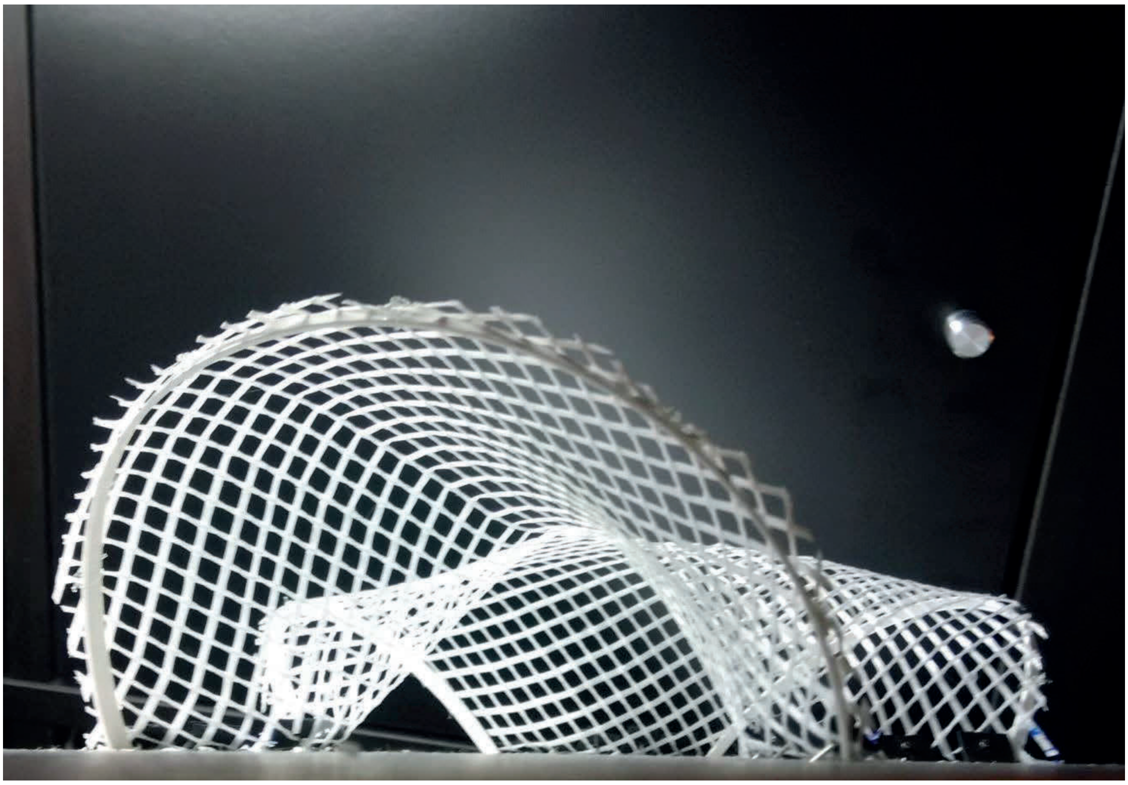

Fig. 2.9 Model created using pushing the edges of the grid [by author]

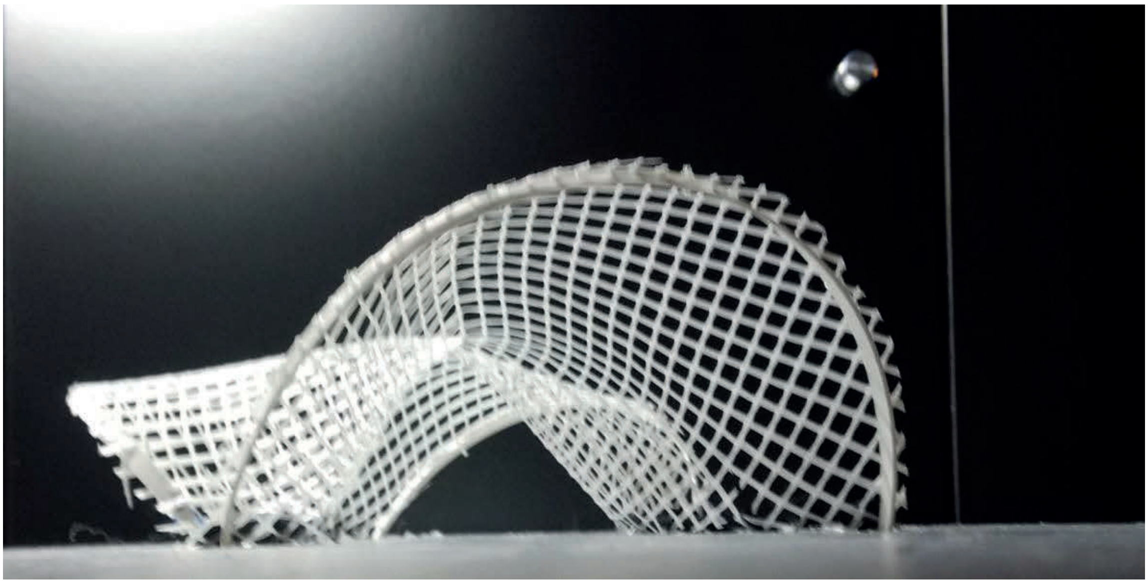

Fig. 2.10 Model created using pushing the edges of the grid [by author]

II. 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.

<u>Hooke´s hanging chain</u>

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. [12]

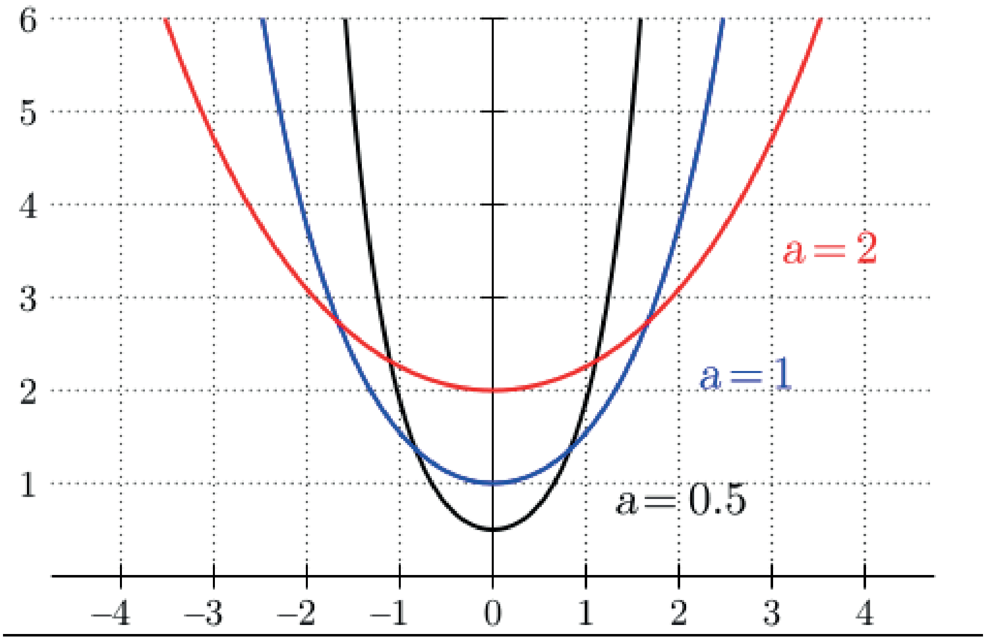

Fig. 2.11 Hooke´s hanging chain principle [12]

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. [13]

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 (Fig. 2.12).

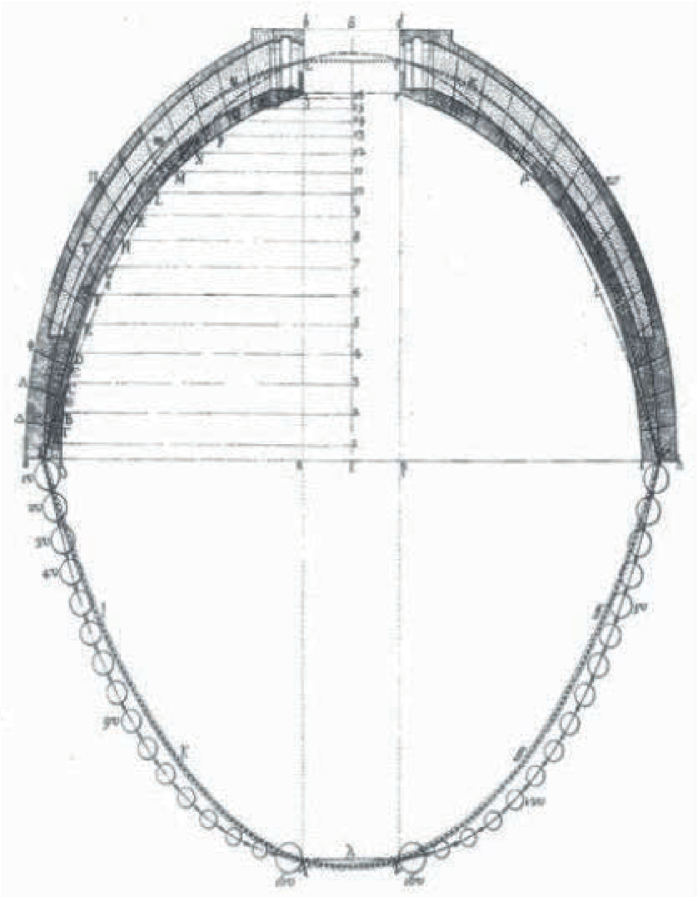

Fig. 2.12 Catenary curvature application – Poleni [14]

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. [15]

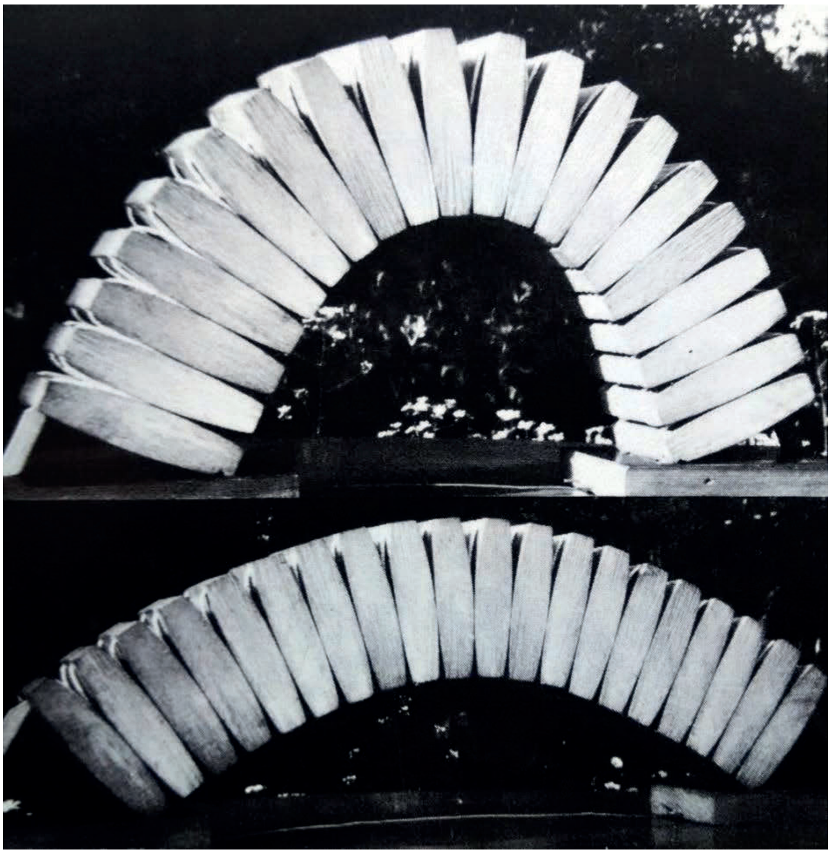

Fig. 2.13 Vault model [14]

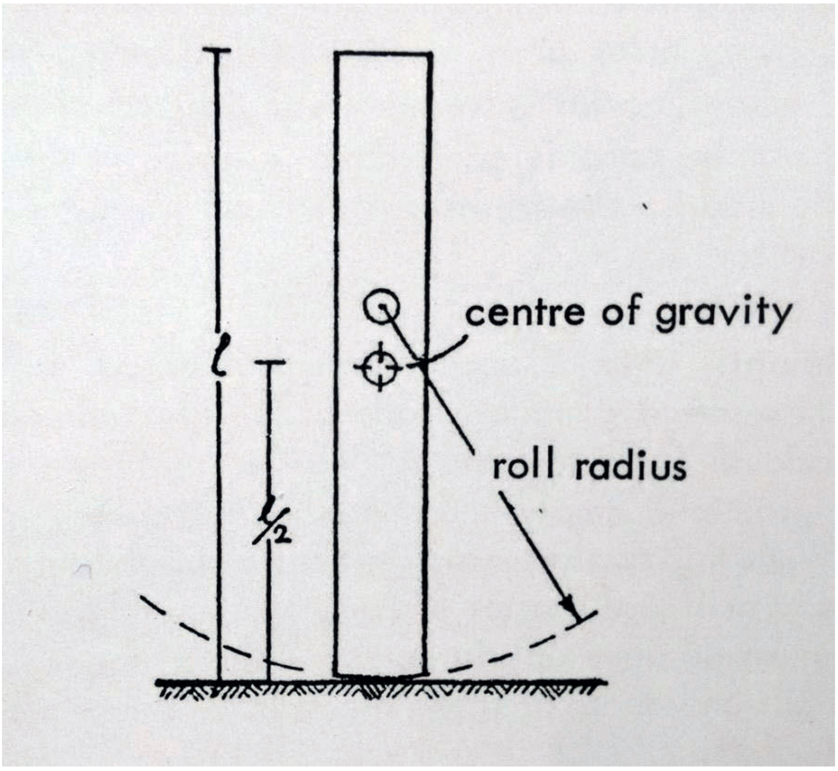

Fig. 2.14 Roll radius [14]

Generally, suspended forms can be made from different mesh material. The only prerequisite is that the mesh must be non-rigid.

Fig. 2.15 Hanging chain model – Most precise physical design technology [by author]

Above mentioned physically based options of form finding are suitable to find the form of a grid shell at model scale. For the full scale structure we need to consider real material properties, which have an influence on final shape and structural performance. These changes in scale can be significant especially in case of small form finding models. In general the larger the mode scale the better the relation between model and full scale structure.

For initial design stages small scale models may be sufficient. However, it is necessary to make larger scale models and prototypes to test the structure and its detail.

III. Compass method: *A square is chosen as the form for the edge. The task is to construct a net within this edge using only a compass. Two arbitrary, curved axes are laid down. The one condition: the axes must intersect. A mesh width is selected and* *serves as the compass radius. The mesh widths are marked off along each axis, starting from the point of intersection of the axes. Thus, three knots of the initial mesh are known: the point of intersection, the neighboring points on each of the two axes. A circle is inscribed around each of these neighboring points – the intersection then serves as the missing fourth knot.*

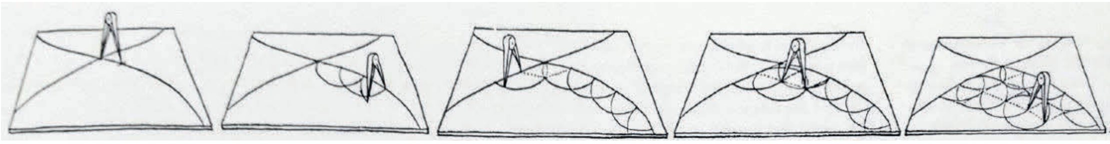

Fig. 2.16 Compass method – Several steps in the procedure [17]

The entire net is obtained in this fashion. Three knots of the mesh to be drawn are always contained in completed meshes. The fourth knot is the intersection of the two circles drawn with radii equal to the mesh width.

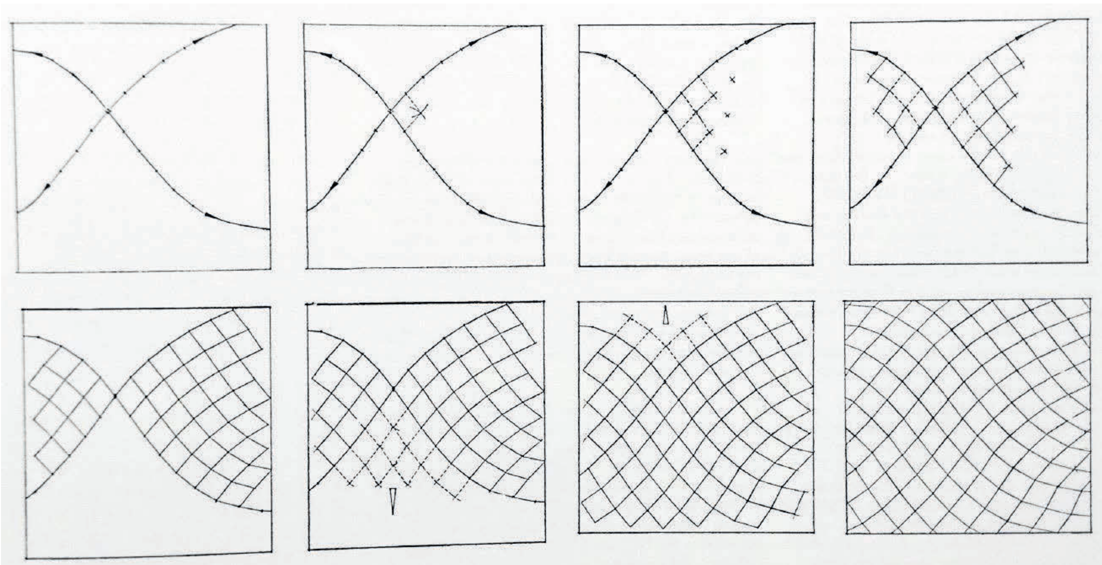

Fig. 2.17 Progressive development of a net within given square edge [17]

This method allows the development of uniform mesh nets on all spatially curved surfaces (Fig. 2.17). It is on fundamental importance when producing the developments of arbitrary bodies. [16]

2.4.2 Computational form-finding

This Master thesis focuses first of all 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. [18]

Following two mainly used techniques:

- **Force density**
  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.

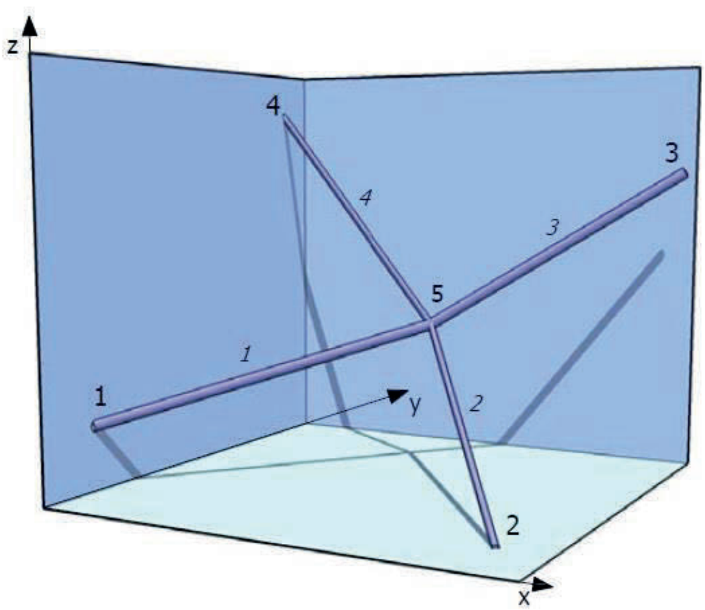

Fig. 2.18 Structure with four members [19]

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.

- **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. [20]

2.5 Cladding of grid shell structures

To understand the cladding possibilities it is important to divide this problem into three sections. Differentiation is made depending on required inner space conditions, typology, weather conditions and usage requirements.

In all cases, using some type of cladding system, solid material or membrane, may also be used structural bracing. On the other hand, when adding cladding to an open grid structures 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.

- **Opaque cladding**

In cases where a grid shell structure covers a space, which does not need lighting from above opaque claddings are used. Typically the grid is covered with wooden planks and after that covered by Waterproof roofing.

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 (Figure 2.12).

It is also possible to apply green roofing though it could be a bit problematic in steep parts of the structure because of material sliding down.

Opaque systems are considered to be mainly used for covered theatres and exhibition pavilions, housing etc.

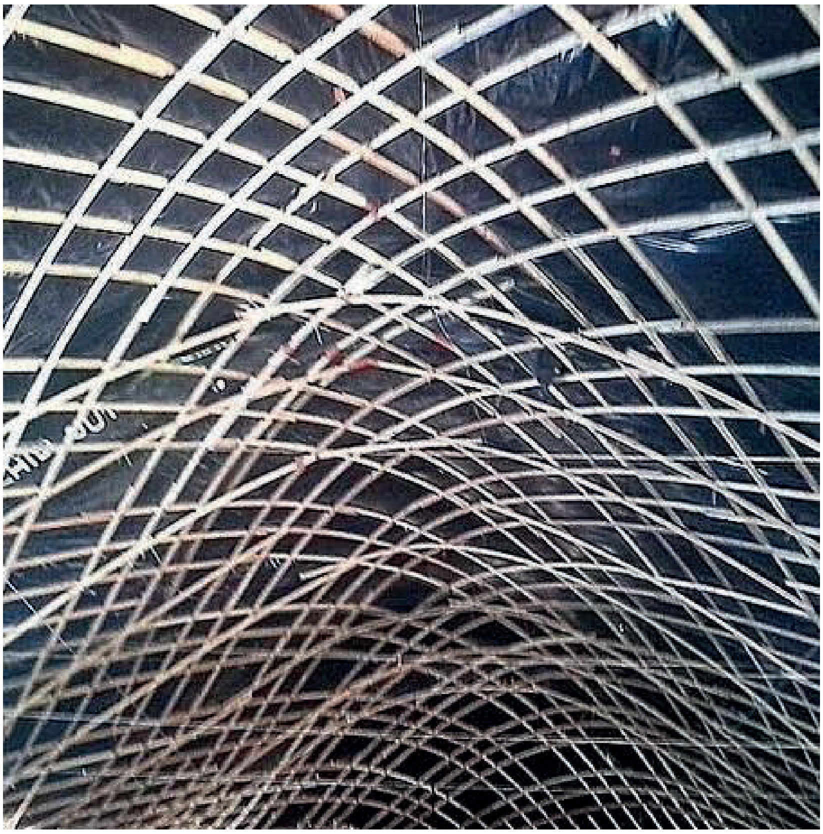

Fig. 2.19 Opaque cladding [by author on 16.7.2015]

Fig. 2.20 Savill Garden Grid shell, 2009 Glen Howells and Buro Happold [21]

- **Translucent**

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. 2.21)

Fig. 2.21 Earth Centre Doncaster, UK – 2010 Carpenter Oak & Woodland [22]

- **Transparent**

Added value may be achieved by using 100% transparent material such as ETFE foil. ETFE can be used as single-layer or multiple-layer air inflated cushions, depending on required inside 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.

In the opened position (Fig. 2.15 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. 2.15 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.

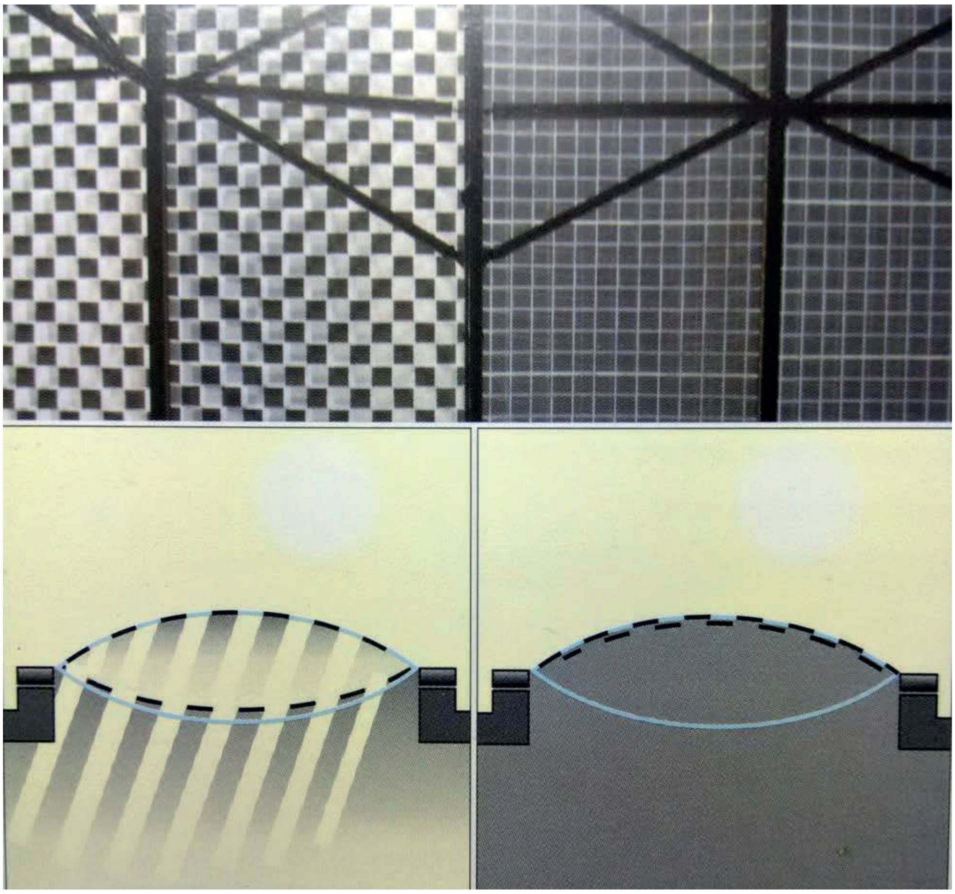

Fig. 2.22 Three-layer cushion shading system [23]

Fig. 2.23 Waitoma Caves Visitors Centre, 2010 New Zealand [24]

2.6 Grid Shell Case Studies

There are many different grid shell projects built in the past, some of which will be mentioned here. The discussion of grid shell structures is a wide topic, each grid shell structure follows an original design approach, has a different scale and assembling procedure, and often uses different details (joints, anchoring, reinforcement, cover cladding etc.). In the current work the main goal was to focus on grid shell with membrane cover, which has only few built examples.

2.6.1 Weald and Downland museum

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. [25]

Fig. 2.24 Weald and Downland Museum - building procedure .[25]

Fig. 2.25 Weald and Downland Museum - completed structure [25]

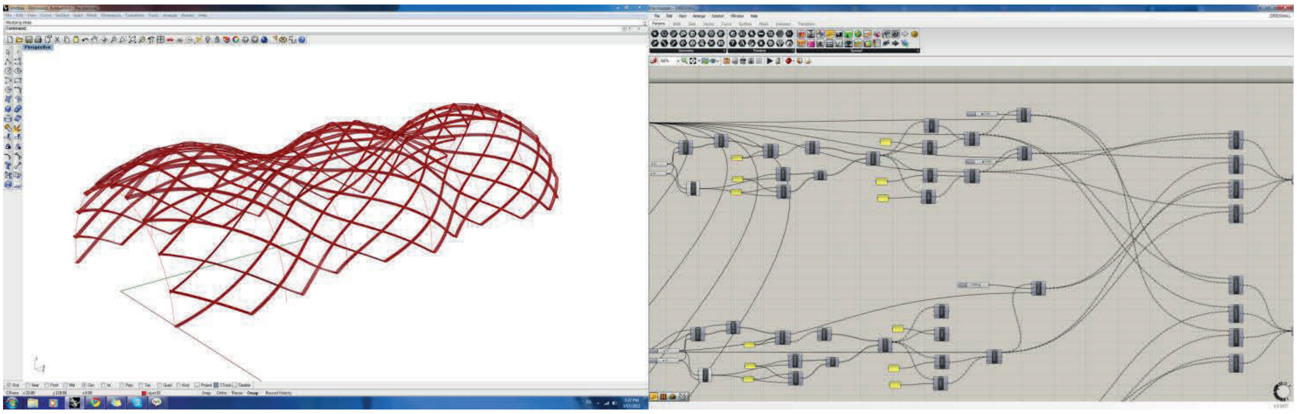

Fig. 2.26 Computer-aided 3D model, Grasshopper definition [25]

Personal comment:

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.

2.6.2 LSRU Grid shell in Sydney

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. [27]

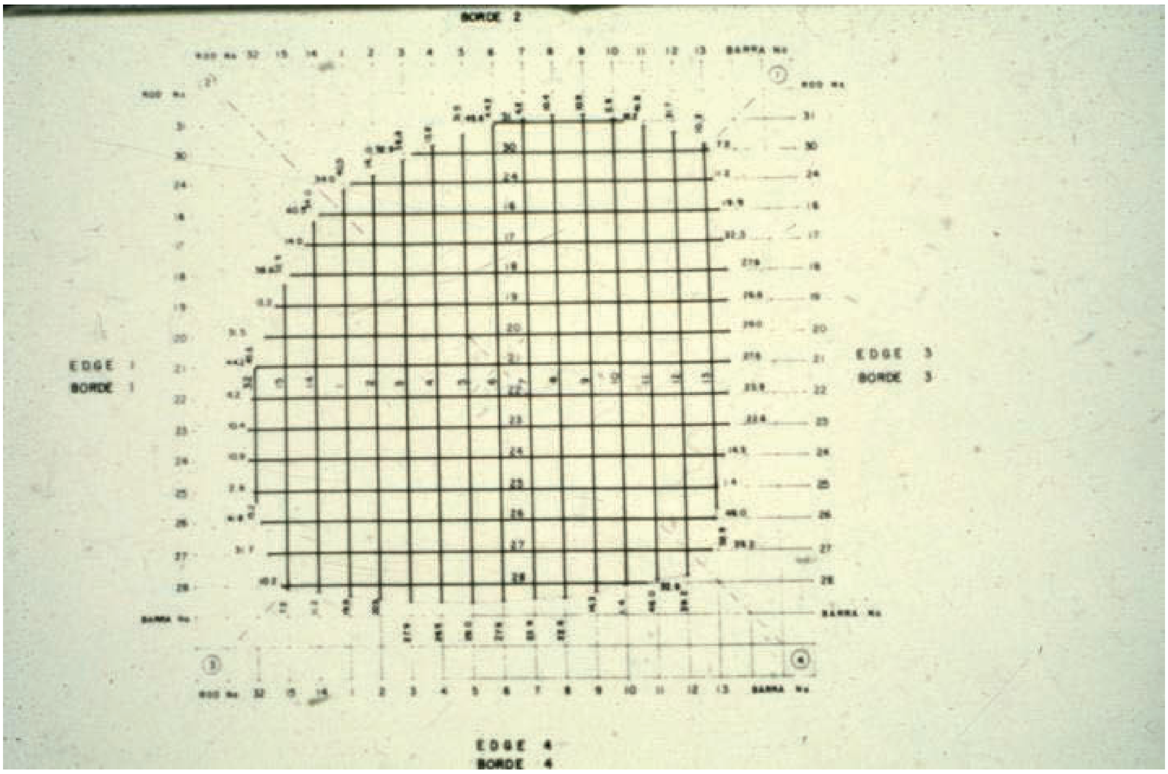

Fig. 2.27 LSRU Sydney 2D Grid plan [27]

Fig. 2.28 Sketch of expected result – one shell leaning against the other one [27]

Fig. 2.29 LSRU Grid shell pavilion assembled and erected, 2nd part before covering [27]

Fig. 2.30 LSRU Grid shell pavilion finished structure at night [27]

Personal comment:

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.

2.6.3 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. [28]

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 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.

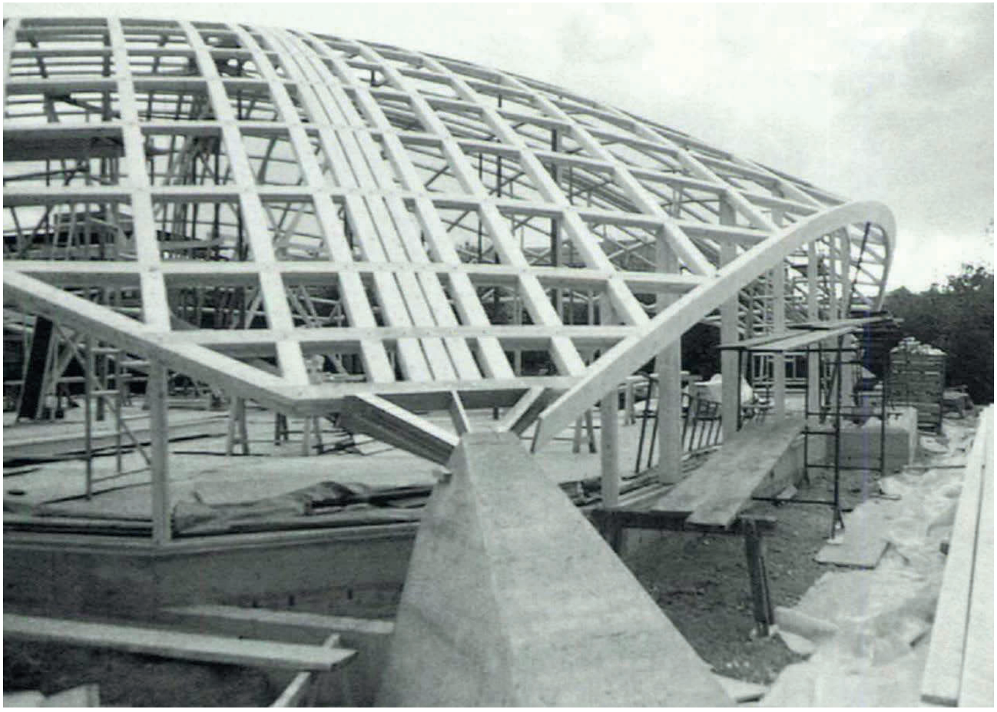

Fig. 2.31 Polydome Lausanne – form at the exterior border [28]

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

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

Personal comment:

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).

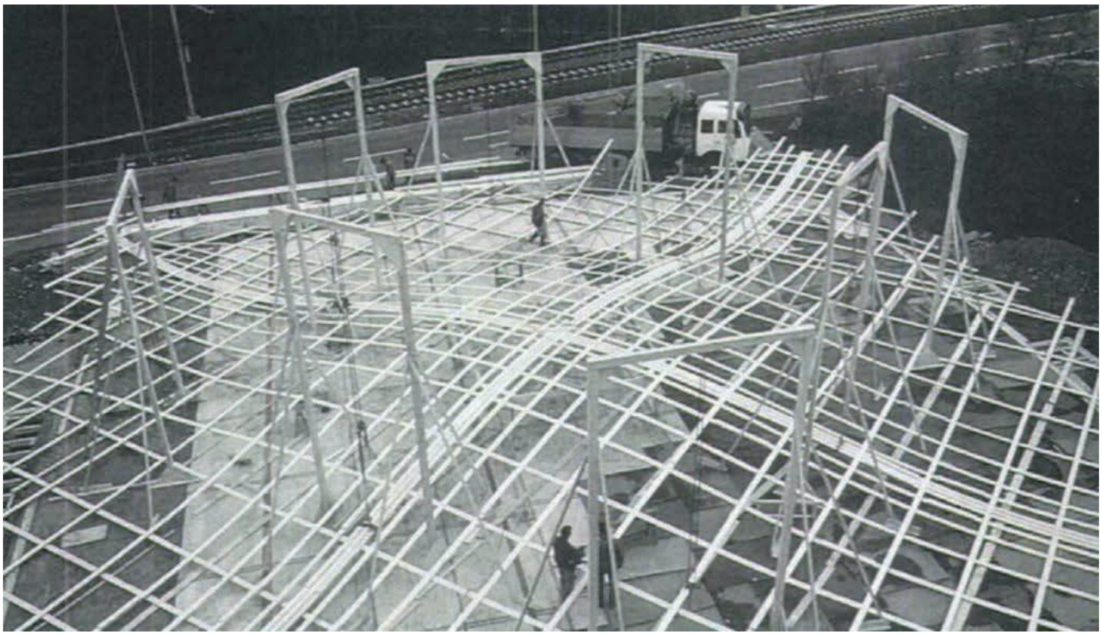

Fig. 2.32 Layout of the ribs at ground level [28]

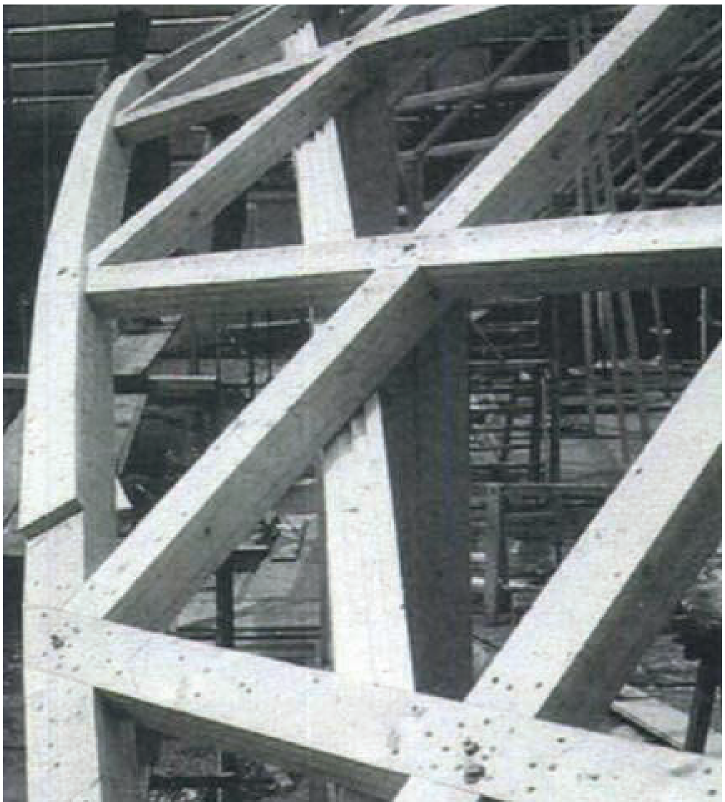

Fig. 2.33 Detail of border beam [28]

2.6.4 House OBU

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

The whole project was a research, 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.

Fig. 2.34 House OBU, outside view [29]

Fig. 2.35 Structure covered with snow in winter [29]

Fig. 2.36 Interior view [29]

Fig. 2.37 Interior view [29]

<u>Personal comment:</u>

This buildings complex signifies a reached dream 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 provoce a new impulse for the architects and become the new way of thinking about what is the meaning about the quality of living.

2.6.5 Workshop in Hooke park

Hooke Park Furniture School workshop was designed in 1989 by Richard Burton of ABK and Frei Otto, with the engineers Buro Happold. The workshop uses spruce thinnings to form a vault from a series of compression arches. The result is a remarkable long-span enclosure built using low-value material from the surrounding forest. Two of the three bays of the roof accommodate a fully equipped timber workshop while the third contains studio space, office *facilities and a small library. is constructed of bent untreated green timber rounds 50-200mm in diameter. These were bent into approximate catenary arches, 3 poles to an arch. 3 conected vaults were formed each of 18 fanning arched ribs, connected by secondary poles perpendicular to these. The vaults bear on 2 RC strip footings & are overlaid with a PVC membrane thus performing like a shell structure.* [30]

Fig. 2.38 Workshop Hooke park interior view [30]

Fig. 2.39 Workshop Hooke park exterior view [30]

<u>Personal comment:</u>

The workshop is an unique structure, which again elegantly and fluently corresponds with the nearest surrounding. Three wavy forms constitutes a spacious working place in the middle of nature with added value of a small library. This structure is well done, especially the interesting double-curvature shape.

2.6.6 Multihall, Mannheim

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]

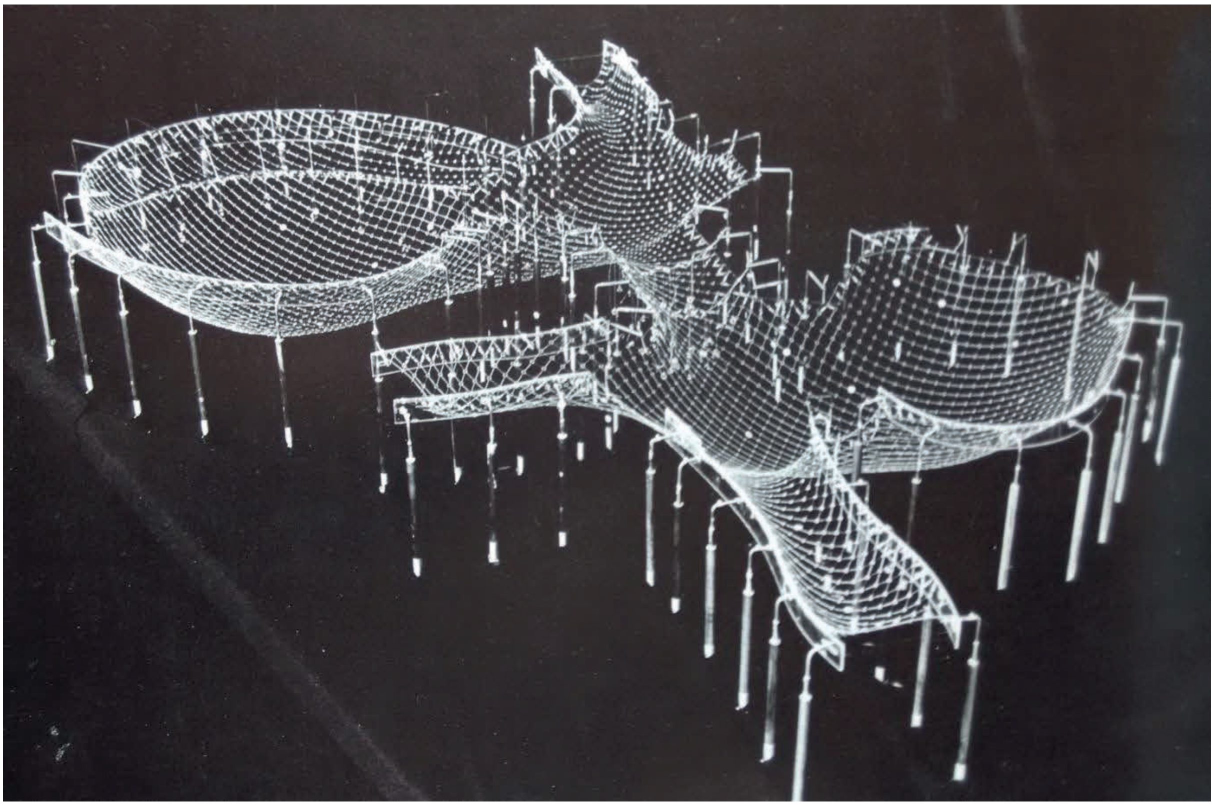

Fig. 2.40 Suspended net model of the Multihall in Mannheim [32]

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. [33]

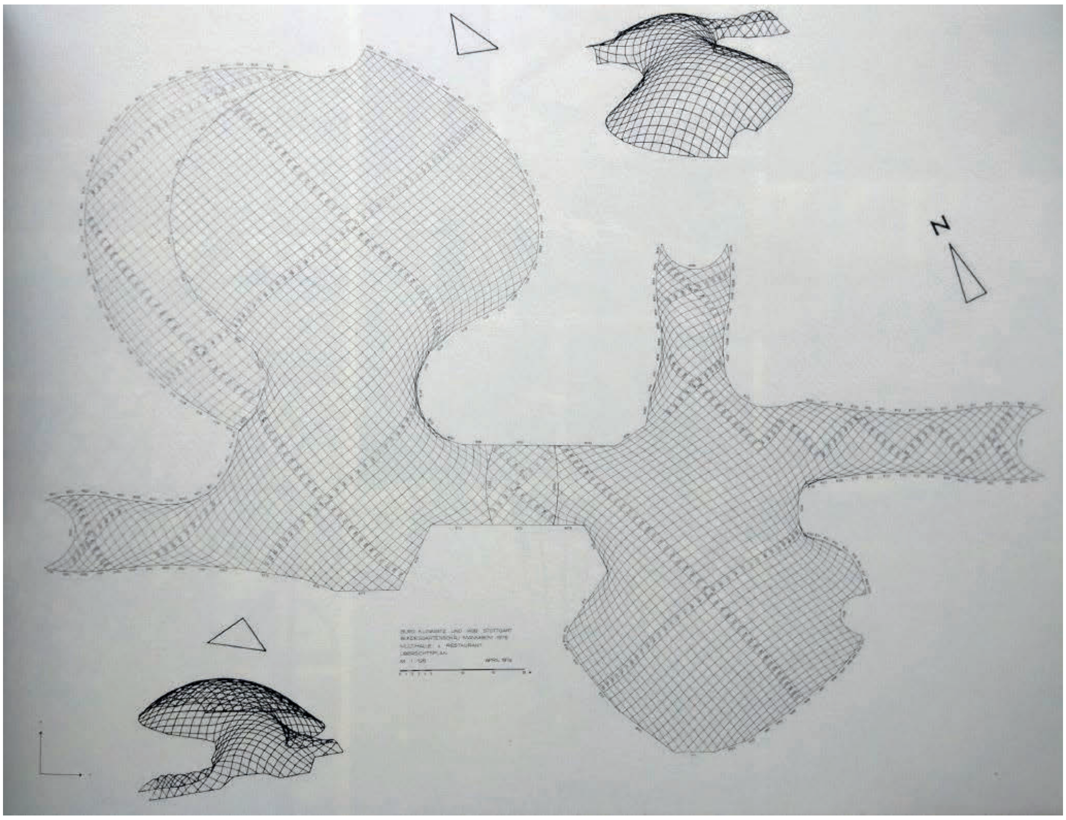

Fig. 2.41 Inverted hanging chain model of the Multihall in Mannheim [34]

Fig. 2.42 Realization of the Multihall in Mannheim [35]

Fig. 2.43 Realization of the Multihall in Mannheim [35]

Personal comment:

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.

2.6.7 Plusminus Pavilion

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.

Personal comment:

This unique design is using negative pressure to fix and reinforce the whole grid which is the lightest possible way to do that, especially in combination with air tubes. The solution is very clever, but needs a lot of caution during the building procedure.

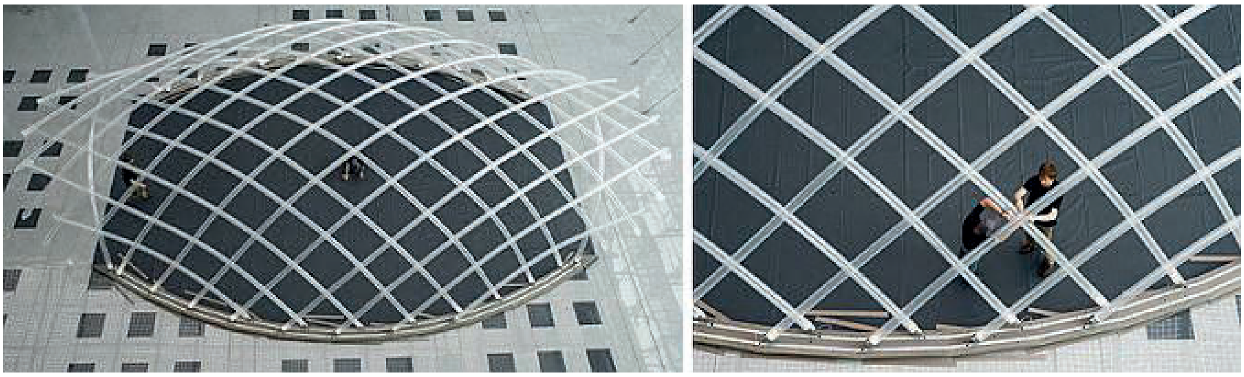

Fig 2.44 Airtubes as a grid shell structure before covering [36]

Fig 2.45 Negative pressure grid shell structure in the entrance hall, Stuttgart [36]

3 Experimental process, different timber testing

The whole experimental process consists of four full-scale experiments. Author´s role was designing, building and supervising. Each structure was designed for a special purpose and fulfilled its function.

3.1 Timber materials, Grid shell experiments

As a first step there was a student workshop organized by the author and in connection to the workshop five experimental timber structures were realized. The goal of this activity was to understand the grid shell in general in a real scale because of having no previous experiences. The basics of such complex structures are best communicated by creating a project from point zero up to the end.

From these experiences conclusions were drawn which became the basis for the Master thesis project. The differences between the built structures were mainly in scale, used materials and erection method. In all cases the same joining system was used. For the Master thesis project were developed some helpful solutions, all of them will be tested in spring 2016. This time is expected to have all necessary permissions from authorities to be able to finally realize the project of covering a pool.

3.1.1 Indoor covering of a sitting place in CTU atrium

This structure was made from dried timber spruce laths 15x35 mm, connected with socket screws, axial mesh square dimensions 550x550 mm, total area 21m². To achieve the 3-dimensional shape, the structure was anchored to existing steel structure, using fabric ropes on the bottom.

This structure was made as an experimental testing sample which demonstrated the behavior of timber grid shells including related problems as breaking, anchoring details, quality of wood, edge solution, chosen joining material, space needed for assembling procedure etc. As a first design project in small dimensions it shows some of main timber properties and qualities. Torsion by bending is an important constituent and with increasing bending of the grid to reach final shape more the torsion was observed in the laths. This is because may be related to an unequal force distribution. In this case longer time would have been needed to find the best erecting procedure. It was working better after some attempts to bring the grid again to the flat position and spread it out again.

Fig. 3.1 Erection procedure [by author 22.5.2015]

Fig. 3.2 The result of first Grid shell form try in atrium of CTU Prague [by author 22.5.2015]

Working with dryed timber provoked breaking of individual laths during the erection process. It is very helpful to soak the timber laths in water before assembling and to keep the assembled grid moist directly after erection. The timber became a bit heavier, but also more elastic for the erection process.

3.1.2 Experimental covering of a pool in front of CTU

Structural experiment as a prototype structure for envisaged realization. Second grid shell workshop took the place under the supervision of Arch. Dipl.-Ing. Jürgen Hennicke, who gave all necessary advices and brought a higher level to the workshop.

His hand made hanging chain was used to find the designed form. Coming out from previously made physical model, which has been used for idea of intended shape, another model was made using the hanging chain method in scale 1:30. This model was subsequently measured and transferred to a real grid. The grid of total surface area 65,1m² made of smooth planed timber spruce laths 22 x 46 x 3000 mm, axial dimensions of squares 500 x 500 mm, each connection using socket screw ø 5 mm + 2 x washer + nut.

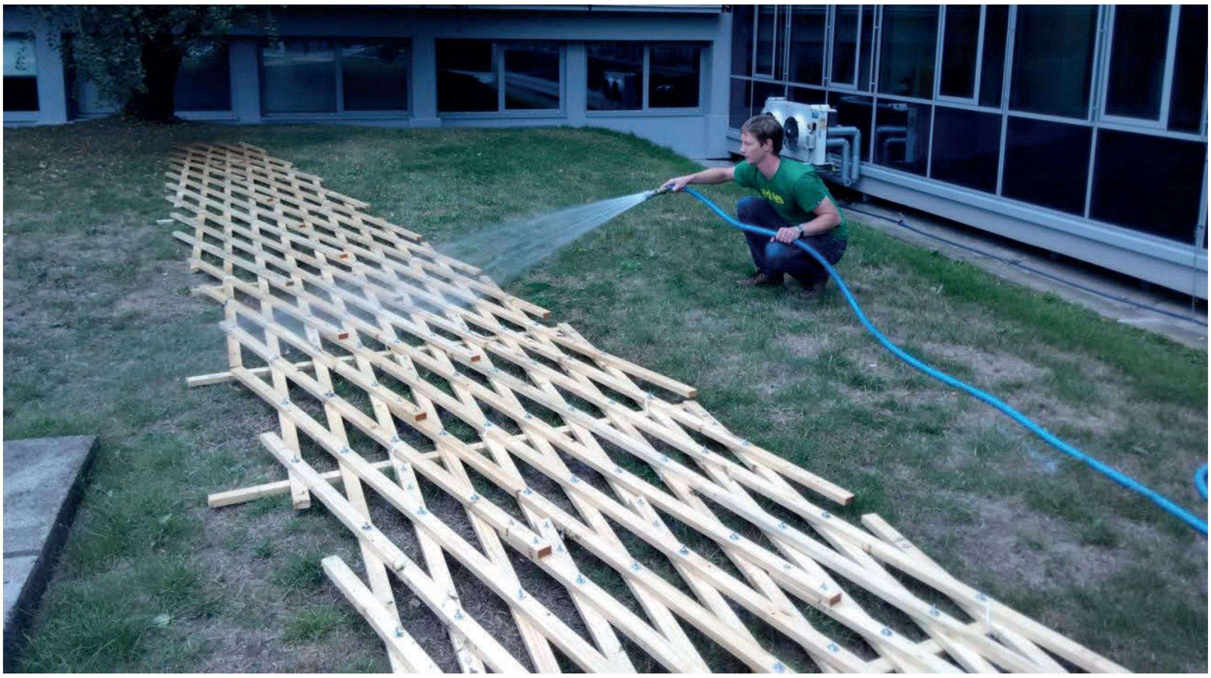

Fig. 3.3 Folded grid, toughen with perpendicular placed laths [by Radomír Vaněk 15.6.2015]

After cutting out all overlaps the final grid was “folded” (pulled from two opposite sides in direction to the middle and fixed with perpendicular laths to reach minimal surface for better shifting), taken to the building side and erected.

There were some difficulties during erection of the structure, mainly caused by supporting procedure with long laths without using proper scaffolding. During erection there were some breakages and unequal distribution of torsion caused the structure to be instable which made it impossible to reach the expected goal.

Fig. 3.4 Example of material failure caused by fast erection (in place of material imperfection)

The other problem was that the workshop was held in 3 days, after this experience it should take at least twice to reach the fundamental shape without additional steps including complete reinforcing and anchoring to the ground.

The advantage of the pool is its graduation – this helps a lot in the anchoring process, because the crucial parts can be fixed. The disadvantage of graduation is more complicated erection process, where is more complicated scaffolding required. The whole grid was afterwards taken off again and placed under the staircase of the entrance, again erected 28.9.2015.

In this case was considered to design a different shape which would be easy to build with 5 people in 1 day. This temporary structure would serve as a pavilion under the trees besides the pool.

The final decision was to erect exactly the same grid to compare it with the first attempt. The situation was been much better, because of previous experiences gained during the workshops before

In case of grass, there are no slippery parts to compare with the pool conditions, the whole structure keeps standing on the edges when step by step pulling the edge line inside the grid.

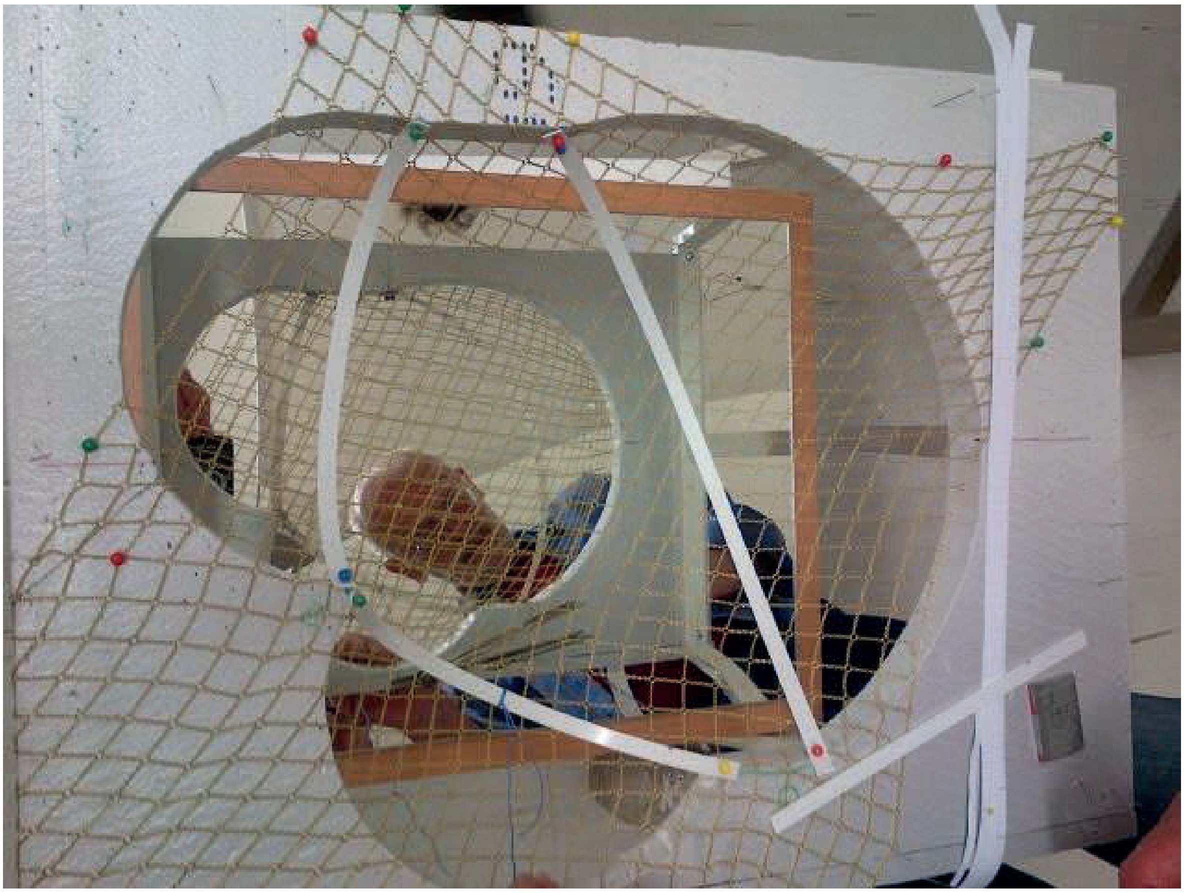

Fig. 3.5 Hanging chain model in scale 1:30,supervising by Jürgen Hennicke
[by author 15.6.2015]

Fig. 3.6 2D grid mesh before the final adjustments [by author 16.6.2015]

Fig. 3.7 Erecting procedure – inside view [by author 17.6.2015]

Fig. 3.8 Erecting procedure – outside view [by author 17.6.2015]

3.1.3 Roof for a temporary theatre for mentally handicapped people

All previously reached experiences were utilized in the next realization of a sustainable temporary project for covering a theatre at a traditional summer fair. The mission was to cover an area of approximately 370 m². The primary structure of walls was made from 115 hay bundles, each of dimensions 900x1200x2400 mm. Altogether for the larch tree timber grid shell roof of 3 tons weight 550 laths of 3m length were used. For the connections details 1600 screws and nuts, 3200 washers were used. This structure was, except for its expanse, not different from previous mentioned structures and used connections.

The pine tree timber as a good choice for this purpose, in comparison to spruce timber has better characteristics and caused not so many breakages. The big advantage by the realization was the possibility to use heavy tools like manipulators and crane. The whole roof was dismantled and erected on the ground and reinforced transversely. The edge was measured and marked out, after that all shifted with the crane sideward to bring it back when the walls from hay bundles were finished. The complete roof area was covered by a simple waterproof canvas, black from inside because of the theatre requirements. Horizontal forces secured by tensioned steel cables.

The timber supplier company Matrix was very interested in such an unique structure and placed an order for a hunting grid shell pavilion from larch timber as a symbol and original element of the company.

Fig. 3.9 2D grid mesh before the final adjustments and erecting [by author 16.7.2015]

The final grid was made from not planed larch timber laths, which weren´t precisely prepared due to the drilled holes they didn´t match together and new holes were drilled on site. This made the realization a bit slower.. There were about 8-10 people working 6 full days to realize the final structure.

Fig. 3.10 Erected Grid mesh, peripheral fixation [by Radek Podorský 18.7.2015]

Fig. 3.11 Roof covering with common canvas

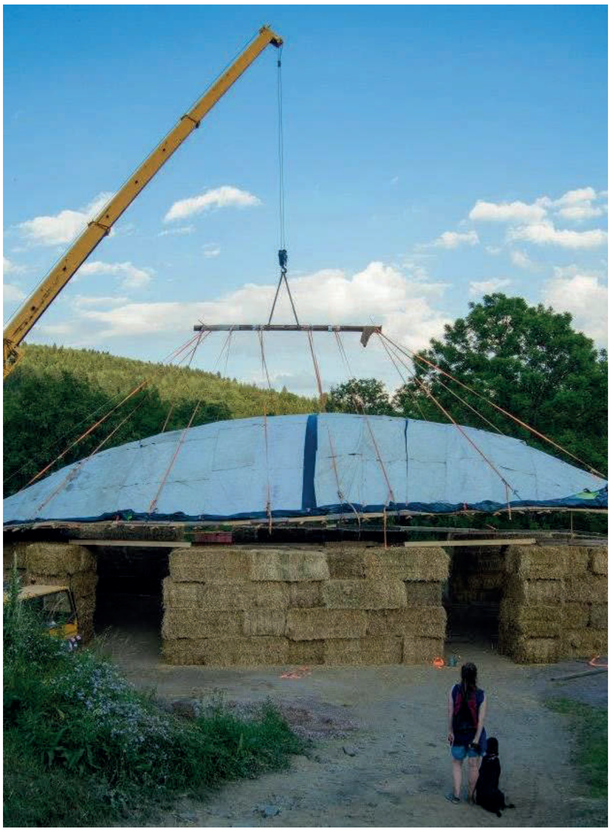

Fig. 3.12 Finishing roof placing [by Radek Podorský]

The grid was first made in the grid density 1 x 1m, in the second step additional laths were added to reinforce the grid in a half of the area. Important to notify that this roofing was build just with a feeling and predicting the structural behavior. When looking back there were some steps, which would be done otherwise next time. For example the workflow - adding additional laths took much longer time as doing this continuously from beginning, because by adding each complementary reinforcing lath the whole grid on the ground floor must be lifted up. In case of big scale roofing this could be quite difficult.

Looking inside to the physical model and to the realized structure we are able to feel the lightness across a big span which makes grid shells irreplaceable in their originality and simplicity.

Fig. 3.13 Physical model interior [by author 20.5.2012]

Fig. 3.14 Interior view [by Radek Podorský]

3.1.4 <u>Mobile shading structure for a seesaw Hojda®</u>

A small grid shell designed for a handcrafted seesaw set made of pine tree laths in 2 widths (23 mm, 45 mm), and 10 mm thickness. This structure may be also used as a shading cover for children´s playground or outdoor sitting cover. The grid could be easily transported by one person, because it is very light. At present it should work only as a summer lightweight shading, because there is not expected using in winter times.

Fig. 3.15 Grid assembling procedure [by author]

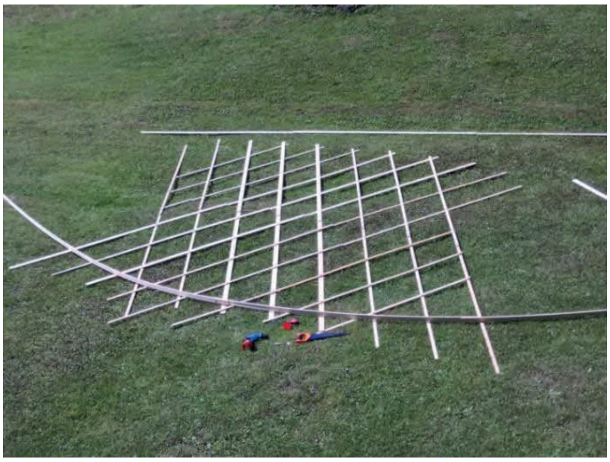

Fig. 3.16 Grid assembling procedure [by author]

Fig. 3.17 Erecting procedure [by author]

Fig. 3.18 Peripheral edges [by author]

There was quite easy design just with a pen and previous gained experiences before mantling the grid. In Fig. 3.15 the erection procedure is shown. As temporary anchors heavy wooden pallets and wooden ladders as pushing element were used.

This cover will be further improved and developed, especially the diagonal reinforcement and covering by a simple single-layer membrane. After all the structure will be tested in wintertime on snow and wind loads (the structure is situated in the Giant mountains in 650 m above the sea level. The snow cover persists there for 4-5 months in a year.

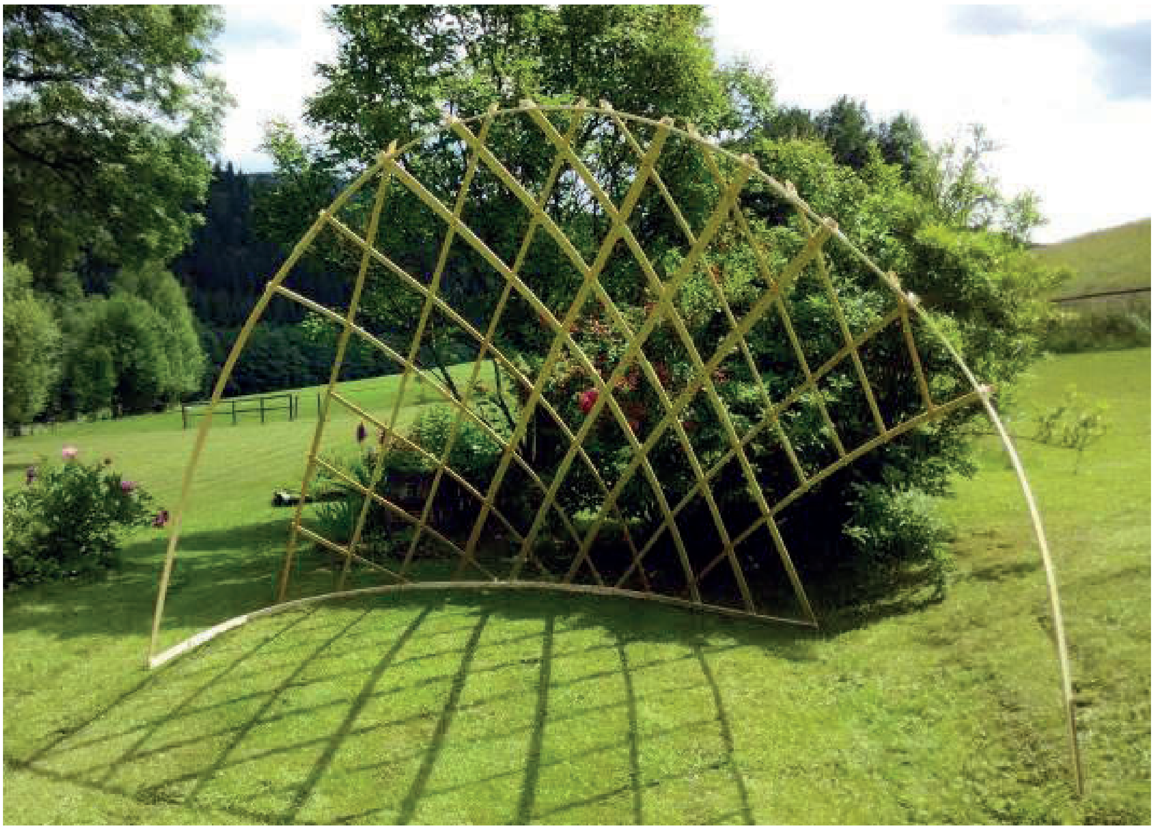

Fig. 3.19 Finished Grid shell cover in the garden [by author]

Fig. 3.20 Finished Grid shell cover in the garden [by author]

3.2 Summary, choice of timber

The experience from the mentioned projects is about using optimally first quality timber with minimal thickness. During all experiments, best crafting was done with pine tree laths of thickness 10 mm and 20 mm widths, continuously treated with water. This guaranteed well bending without breakages, better behavior during erecting is possible to achieve by sprinkling water on the prepared grid a few hours before erecting.

When doing the drills it´s always necessary to be very precise and careful in handling the laths. From my experience, using spruce timber is not advisable because of its qualities, but when being careful and patient during erecting, it´s also possible to create an interesting double-curved shape.

The best material which was able for the tests was larch timber. It does not have so many knots and is possible to bend in higher values, because it contains high percentage of resin.

The disadvantage could be in manufacturing, because of aggressive resin. One has to be careful about that and use protecting gloves, which is unpractical when joining. When using oak timber, it is necessary to use high quality bolts. This material is aggressive to metallic parts and could cause corrosion.

As next problematic subject in designing grid shell structures is considered the timber cross-section. There is an ideal case when using round cross-section, because of the same behavior in both directions by bending and torsion.

4 Project design procedure

This chapter deals with the whole process of design procedure from the site description across finding best suitable structural solution, form finding, building physical models and material testing. Chapter 4 is considered as one of the most important in this Master thesis.

4.1 Construction site description, location characteristics

The construction site is positioned nearby the main entrance to the Faculty of Civil Engineering in Prague, exactly in the corner of buildings A and C (see Fig. 7.3). Building A with cabinets and lecture rooms in 15 stories is the highest building belonging to CTU, building C with 2 stories contains the main entrance, lecture theatres and study department, in the middle spacious a atrium covered with the glass roof.

The pool is comprised of two connected parts, each with different depth and a total area of 189,5 m². The perimeter of 57.6 m consists of concrete slabs, each slab 1,6 x 0,8 m in ground plan.

Fig. 4.1 Pool present condition [by author]

Fig. 4.2 Pool present condition [by author]

4.2 Suitable shape solution

There were no other designs made for the pool covering until now, which means there were not any inspirations of previous designs. The shape came up with the requirements for a clean, representative and functional pavilion.

4.2.1 Orientation

The design was made according two main topics. As seen from the ground floor plan (Google maps screenshot), the speculated area around the pool is south oriented, on the nord-east and nord-west side are situated buildings A and C. This means the area is very illuminated, which is comfortable for having a nice lunch time. In the concrete pool, there is the need of a lightweight structure, which wouldn´t constitute a visual or materialistic barrier. At the same level there´s need to provide shading cover, which is also capable to withstand rain and resist wind and snow loads. The structure has three main arches, the biggest one with the maximum height of four meters from the pool bottom oriented west and two lower arches in directions south-east and nord-east.

4.2.2 Use and scale requirements

First requirement (a bit overstated and amusing) from the College authorities was to build up a structure for smoking students to offer them a nice place to enjoy their bad habit instead of be standing right in front of the main door. The cover should protect from rain and should drag them out of the main entrance, where they are quite a disgusting barrier for people coming to the College building. The concept is primary taking to account all students, Faculty employees and people passing by to offer them a nice place to relax and enjoy prospective culture event.

4.3 Form finding – Physical model

As already mentioned, in case of Grid shells in every even simple design a physical model is of high value. Creating physical models keeps the designer close to a possible, reasonable and feasible form.

For the first models without many previous experiences were used paper and plastic stripes. 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.

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.

The next step to verify feasibility is material testing. The aim was to verify if chosen material is applicable for the structure. The test was made by bending connected spruce timber laths measuring reached height until the breakdown (Figure 4.12, 4.13, 4.14).

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

Tested sample result:

$R = (7{,}25 + 4x1{,}26^2) / 8x1{,}26$

$R = 5{,}8m$

Because of inhomogeneous timber behavior we use the safety factor of 1,5. This means that the value of R = 8.7m can be taken into account (bigger radius = smaller curvature). This value depends on type of wood, its humidity, thickness and joints length.

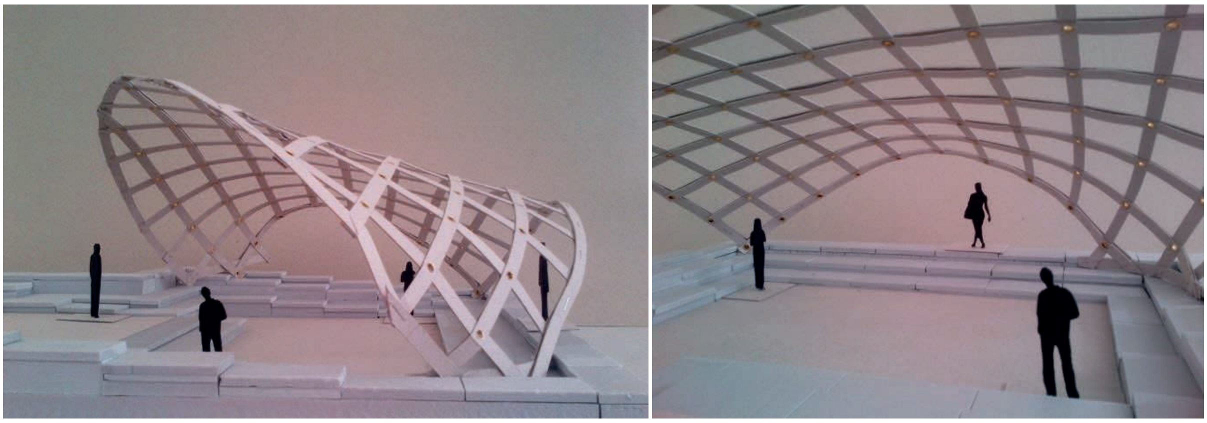

Fig. 4.3 First physical model from paper [made by author 02/2015]

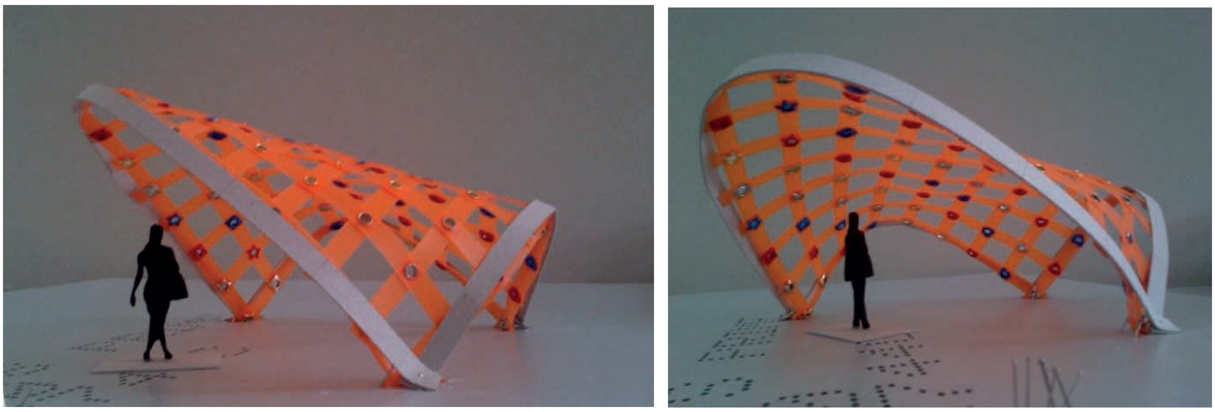

Fig. 4.4 First physical model from plastic stripes [made by author 02/2015]

The biggest challenge in the experimental procedure was to connect single „stripes“ between each other in crossings. Big advantage doing physical models is the ability to work in small scales compared to other types of lightweight systems as single-layer membranes or pneumatics.

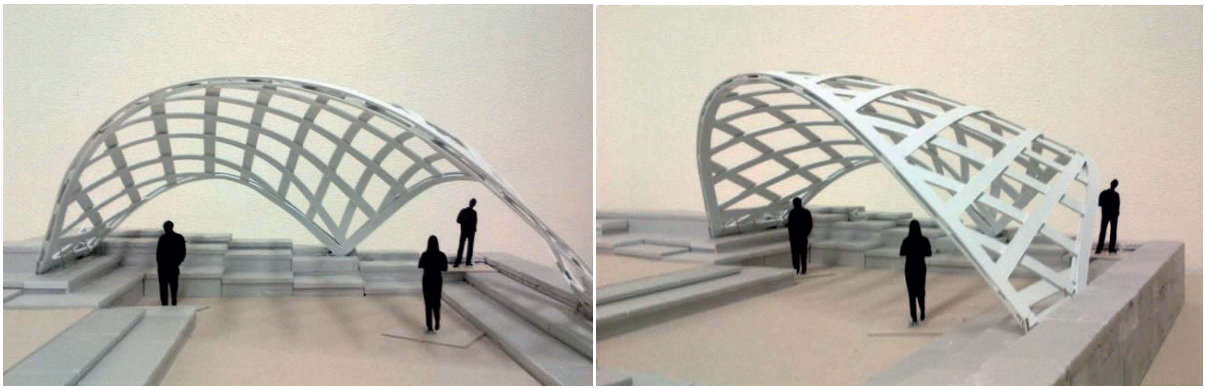

Fig. 4.5 Final shape physical model [by author 03/2015]

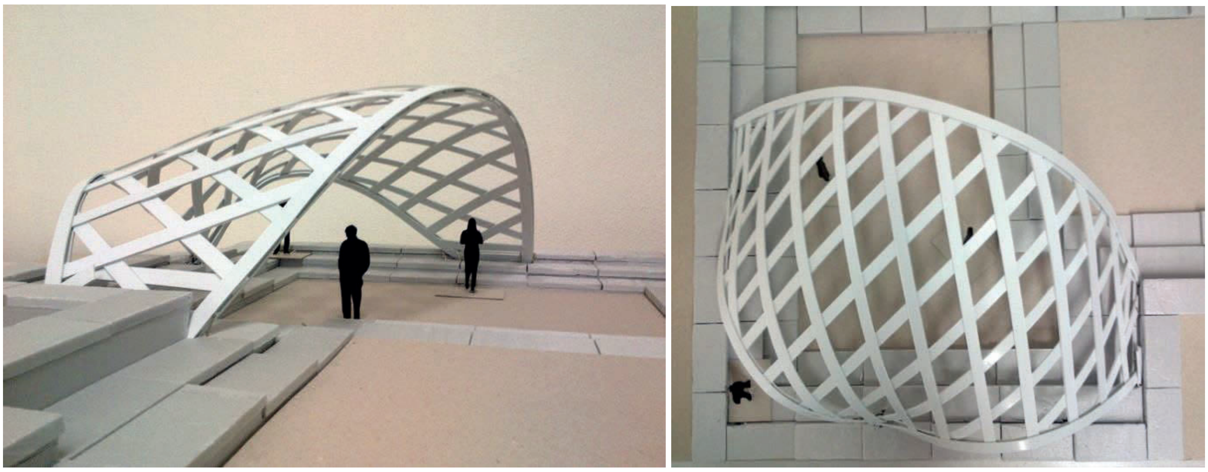

Fig. 4.6   Physical model made of hardened polystyrene (HIPS) stripes glued together [by author]

By building a physical model using the HPS, there are not many feasible ways making the crossing movable connections. It proved to be practical to use a punch–plier set and punch and connect every 2nd hole (Fig.2.7).

A disadvantage for this method is of the inevitable wrong grid scale, which should have a width of 2 mm instead of 9 mm (Fig 4.7). This means additional element size is stabilizing the structure. A real scale model would give the impression of four times lighter and more elegant structure, which is partially possible when using a suitable modeling mesh.

Designing a grid shell is nowadays still possible without using any kind of software, but it is very helpful to have one for further structural analysis. First steps were comprised from making a proper physical model. The model was measured by counting the chain parts and the final grid shape determined. After that the grid was projected to the ground plan and transformed to the digital form using AutoCAD (Fig. 4.14).

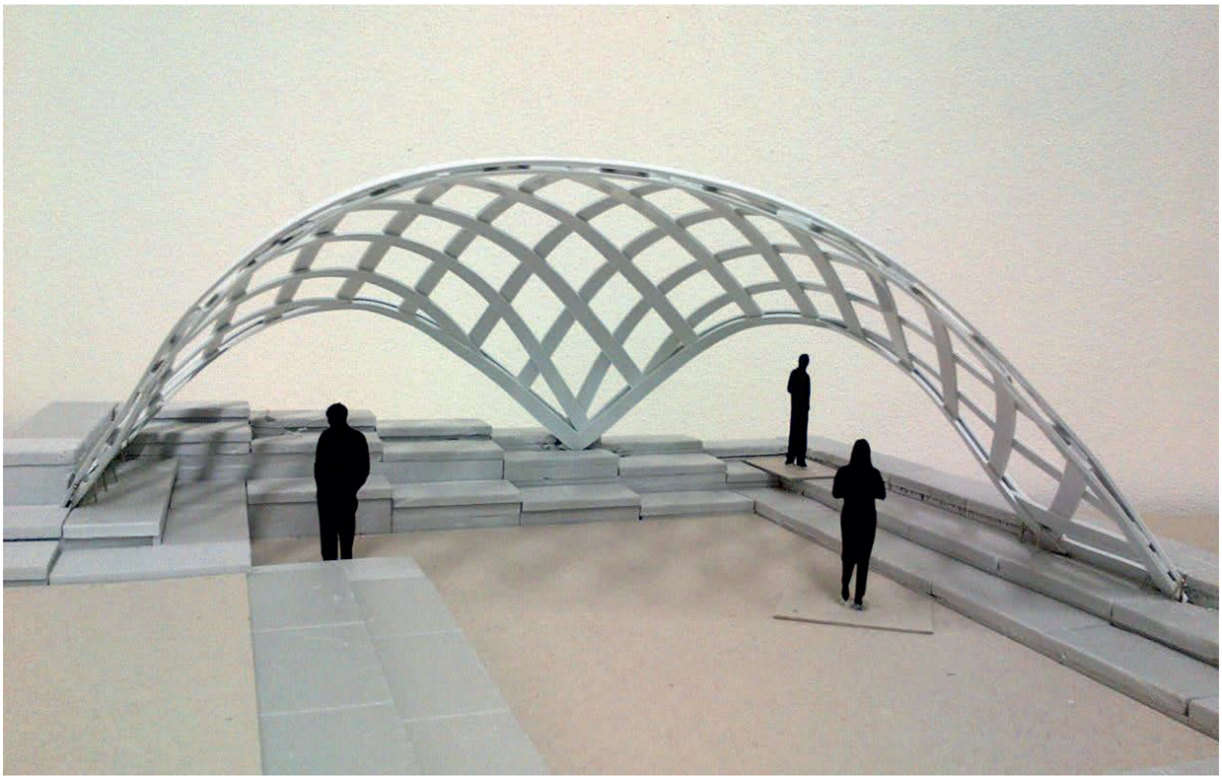

Fig. 4.7 Physical model made of hardened polystyrene (HIPS) stripes glued together [by author]

Fig. 4.8 Basic mesh top view from hanging chain form finding [by author]

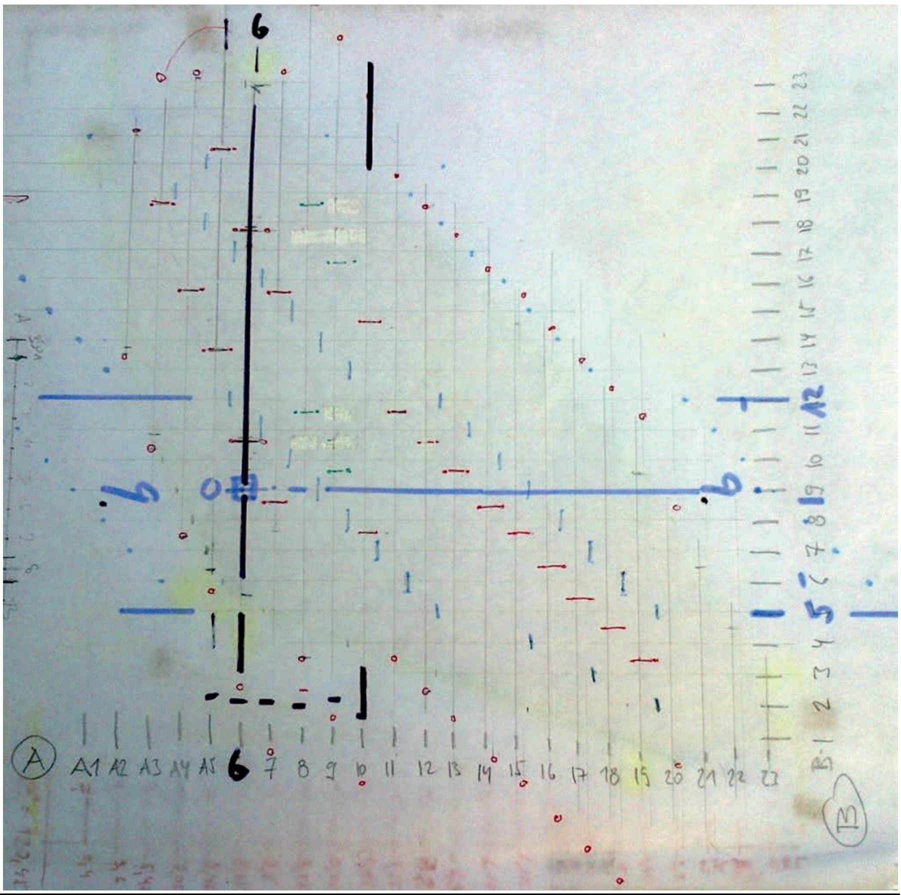

Fig. 4.9 Mesh top view timber longitudinal joints summary [by author]

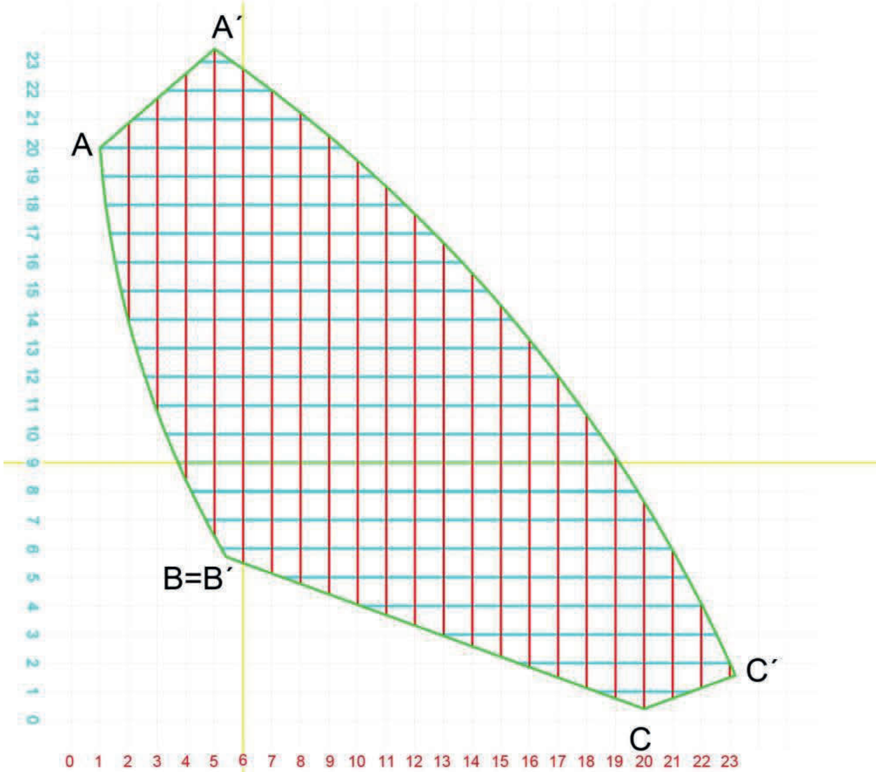

Fig. 4.10 The final 2D mesh top view from AutoCAD [by author]

RED lines

line no.	length total	length L	length R
1	0	0	0
2	3600	0	(+)2350
3	5450	0	(+)900
4	7050	300	6750
5	8450	1225	7225
6	8650	1750	6900
7	8500	2000	6500
8	8250	2150	6100
9	8050	2400	5650
10	7850	2600	5250
11	7550	2750	4800
12	7200	2830	4370
13	6900	3000	3900
14	6550	3250	3300
15	6200	3375	2825
16	5750	3525	2225
17	5300	3750	1550
18	5000	4000	1000
19	4450	4200	250
20	3800	(+)500	0
21	2850	(+)1250	0
22	1550	(+)2250	0
23	250	(+)3500	0

BLUE lines

line no.	length total	length L	length R
1	1750	0	(+)5950
2	3800	0	(+)4650
3	5050	0	(+)3150
4	6300	0	(+)1700
5	7350	0	(+)375
6	7850	375	7475
7	7850	600	7250
8	7800	825	6975
9	7800	1100	6700
10	7650	1350	6300
11	7500	1550	5950
12	7250	1750	5500
13	7100	1875	5225
14	6850	2050	4800
15	6450	2150	4300
16	6150	2250	3900
17	5550	2350	3200
18	5250	2450	2800
19	4800	2500	2300
20	4200	2500	1700
21	2850	1875	975
22	1750	1325	425
23	600	0	(+)150

Fig. 4.11 Lengths of the timber laths – counted from physical model

4.4 Material testing

Because of dissimilar material properties there is need of doing tests. Focused on timber, the first test is very simple and does not need special tools when using visual quality estimation. Convenient timber is straight and does not have much (or any) knots. Bending tests are necessary after joining the timber laths lengthways. In this case we bend at least two connected laths of average quality until breaking point – this gives us the maximal curvature value.

From the experience we cannot take the minimal bending radius as determined through the tests, because in reality we bend the whole grid, which is not able to reach this radius at all. This test is more about the flexibility of chosen timber and its joints, in most of tests the lath breaks nearby the joint. By overlapped joint it´s almost impossible to get the breakage directly in the joint due to doubled cross-section.

Fig. 4.12 Timber bending testing [by author]

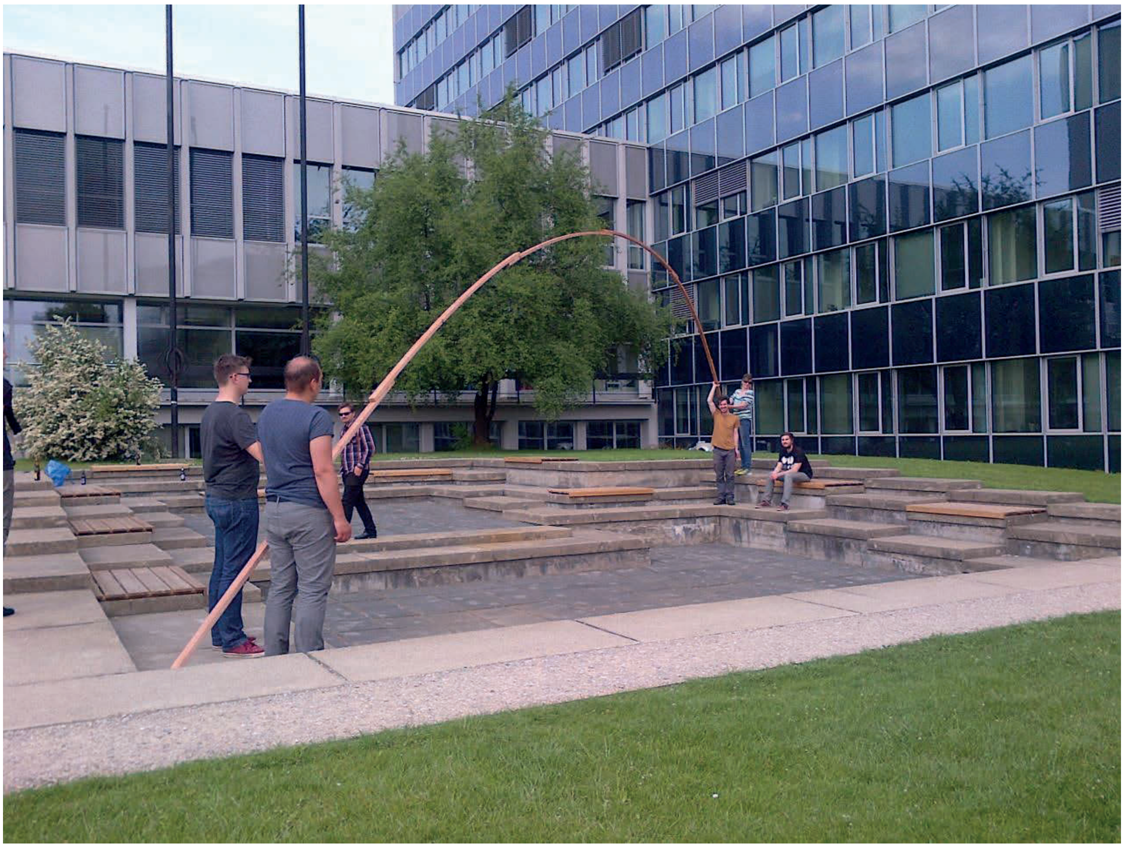

Fig. 4.13 Timber bending test [by author]

Fig. 4.14 Testing result – breakage near to the longitudinal connection [by author]

4.5 Structural solution

For the pool cover it was chosen to install a grid shell structure, which is able to form using flexible material (wooden laths) and connection joints. The structural principle is based on using continuous laths in two directions, connected in their points of intersection. The final shape is achieved by erecting the whole structure, by bending area squares in ground plan grid changed spatial shell shape in space.

After reaching the requested shape the perimeter is fixed and all joints tightened.. For a precise result and to avoid unfavorable behavior in timber (bending, torsion) it is important to choose the right system by connecting the laths to reach required length (connecting shorter timber laths in between is necessary due to complicate transport and manipulation of long ones, there also wouldn´t be possible to reach required length from timber producer). By designing the first experimental structure overlap joints were used.

5 Used structural details

There are in chapter 5 described structural details used in authors full scale realizations. Also there are some other solutions mentioned, which could be used later on by following experiments.

- *Laths length connection*

For the first experiment, overlapping joints were used with a length of 300 mm, connected with two screws with flat rounded washer (ø4 mm, l=65 mm).

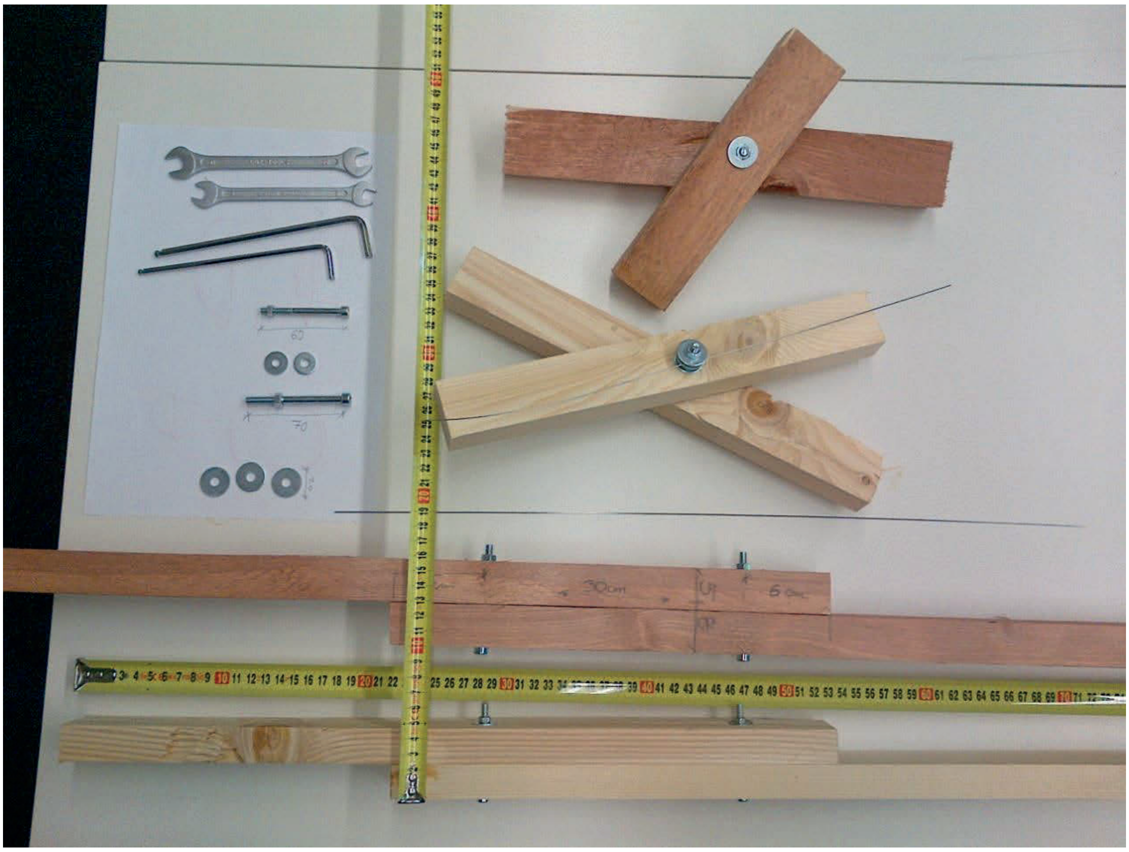

Fig. 5.1 Connection joints testing [by author]

For the final structure design finger joints are speculated. This type is more difficult to assemble and the time for glue harden quite long (approx. 24 hours – it is required to assembly by good weather conditions to avoid longer necessary time for well dry out), but it is considered to be the cleanest possible way to achieve a smooth surface without head-butts and additional excentric forces which could cause breakages by erecting and setting up the finished timber grid. Finger joint producers present as an advantage:

- The glue joints are engineered to be stronger than the actual wood fiber
- Stays straighter than solid-sawn dimensional timber
    - Less flection
    - Less bending
    - Less twisting

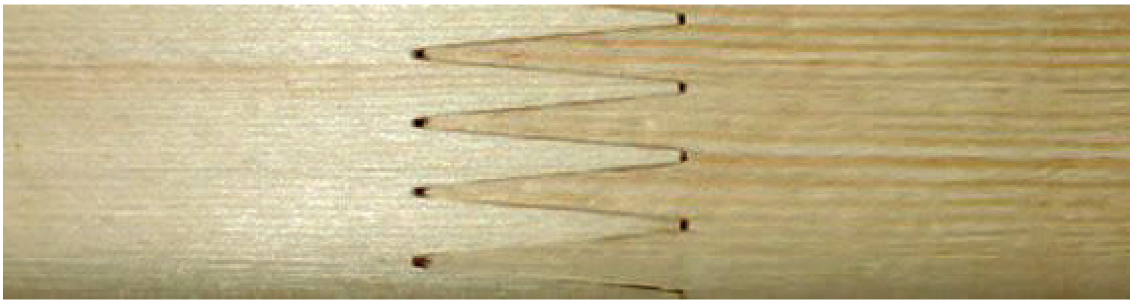

Fig. 5.2 Finger joint [by author]

It is possible to use many different materials with other joining types, for example long hard plastic tubes one side widened for sticking together, which could be a topic for a coming workshop.

In case of round cross-section material (round timber, round plastic tubes etc.), other joining types are used, due to the:

- *Intersection joints*

The grid cross connection is designed in every intersection using one hex socket screw with half-rounded head, nut and two washers. Each drilled aperture must be precisely measured, marked and drilled with a special drill for timber.

- *Anchoring to the bottom*

For sufficient stability the whole structure anchored to the ground every 1,5–2 m. For holding the horizontal forces from the grid shell there will be used peripheral stairs, stacking anchoring segments. After that each anchoring part will be fastened using chemical anchors.

Fig. 5.3 Intersection joints detail [by author]

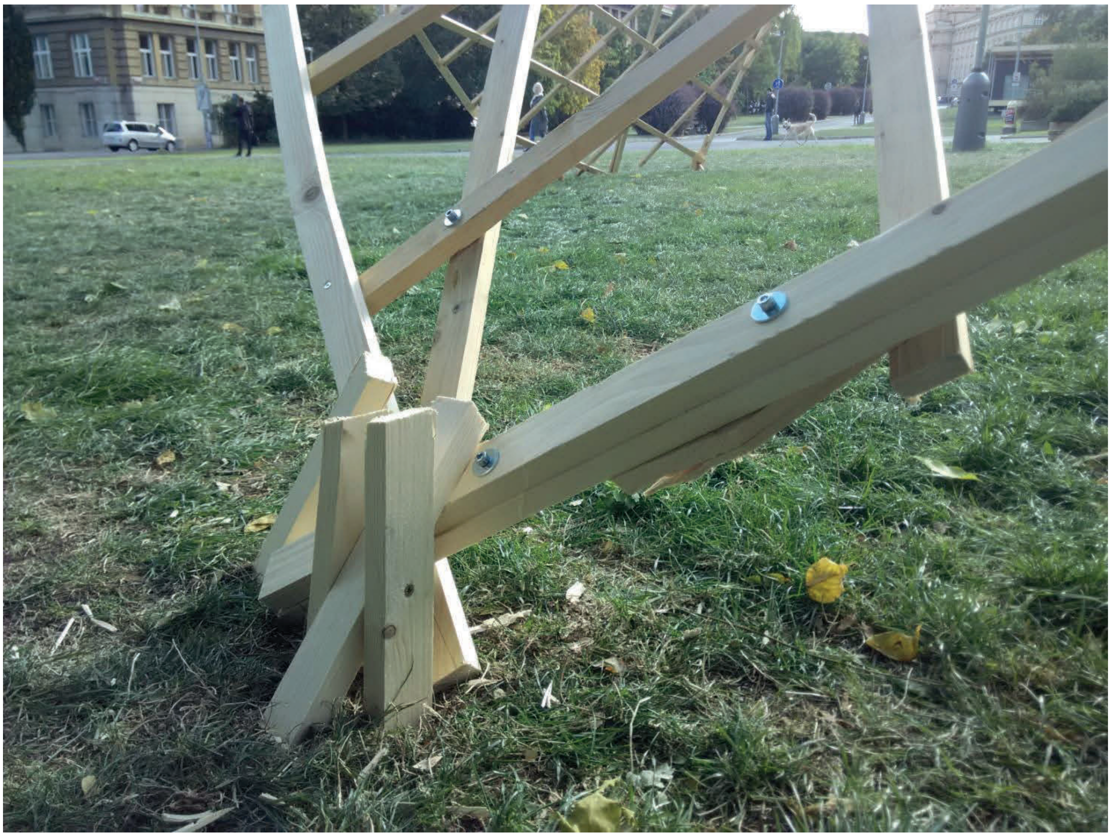

Fig. 5.4 Anchoring to the bottom [by author]

The experimental structure was made on the green field besides the pool to be able reach the final required shape. The anchoring was made from same laths nailed into the soil. The grid is tightened using screws.

- *Bracing of the Grid*

The final structure shape after all screws are tightened still needs bracing to develop its full shell capacity which per definition can transfer both normal and shear forces. The following methods may be used for bracing:

- Additional laths layer in one diagonal direction
- Cross bracing with cables e.g. Dyneema® ø2,5 mm
- Fabric membrane with coating – single layer, mechanically fastened
- ETFE cushions - double layer inflated elements
- TPU foil (thermoplastic polyuretane) - double layer vacuumed (technically demanding method).

Ideas for original solution:

After consultation with specialist from Serge Ferrari was as a suitable material for potential covering chosen the PVC coated PE fabric – Précontraint 1202 S2.

From functional, aesthetic, economical and safety reasons there should be covered about 65% of the structure area, the rest will be braced using Dyneema ropes or timber laths. Because of membrane cover there is an additional need to achieve a smooth surface to avoid membrane tearing.

6 Assembling and erecting procedure

Before the erection of the structure it is important to get the construction site ready. There is the need of plain surface without any barriers and large enough predicting spreading out and shrinking the whole grid. Demarcation and securing of necessary space for construction procedure, setting up an information panel for spectators. Before each erecting step everything must be clear for everybody, because the grid must be erected uniformly and gradually step by step. The main workflow will be going on in several following steps:

- *Creating basic coordinates system*

This step is carried out using a colored high-light spray to marc the space necessary for placing the whole grid shell into a plane. Instead of placing the basic grid as a rectangular mesh it is possible to shift the mesh angle and set up a rhombic mesh – this is possible if little space is available. To compare with a rectangular mesh it does not cause any problems if the holes in laths are precisely drillt. Placing the basic grid with too tight angles could cause problems with dearth of space by assembling the grid. This has an impact by placing further layers.

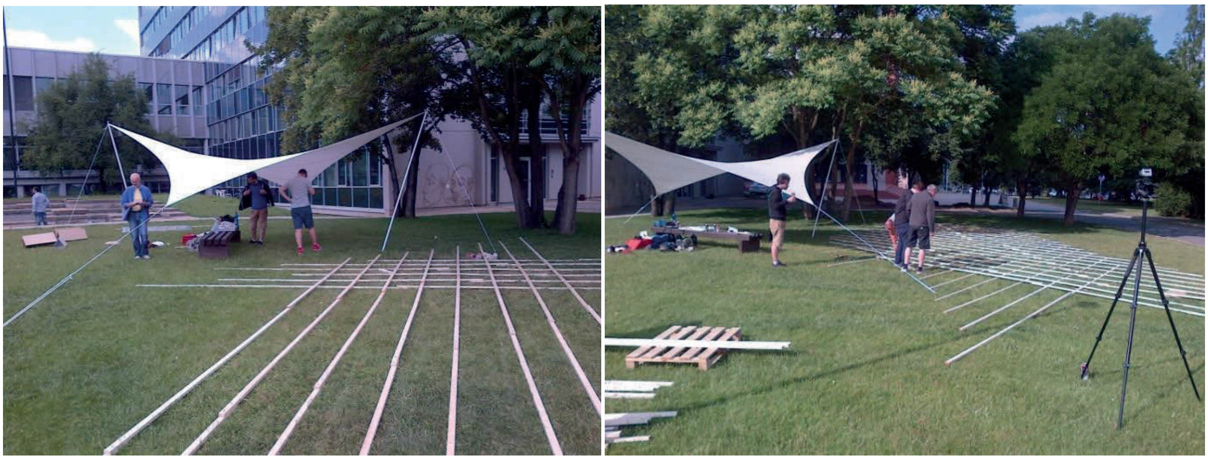

Fig. 6.1 Two layers of timber grid done step by step [by author]

- *Assembling the whole timber grid*

After setting up the main coordinates the first layer is laid down. It is necessary to check each line, because the whole system is becoming less readable due to requisite overhangs on both sides.

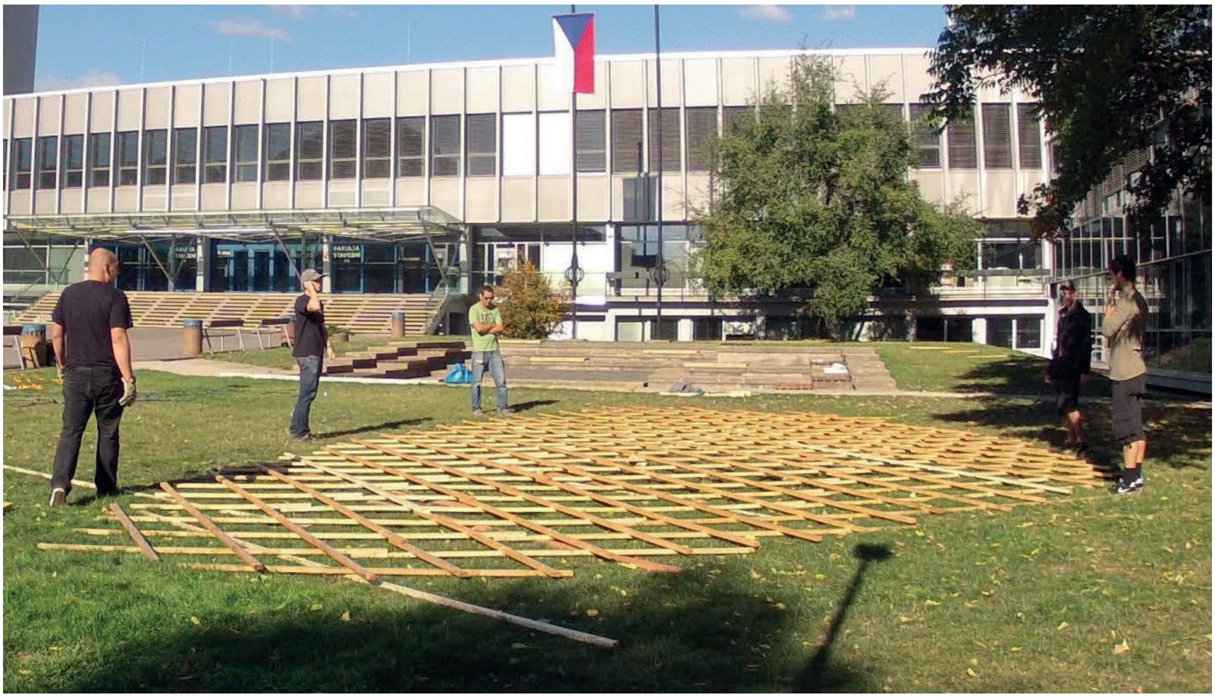

Fig. 6.2 Two layers of timber – grid shell ready for erection [by author 28.9.2015]

- *Setting up scaffolding / tool to lift up the whole grid*

One of the last and most exciting parts of whole procedure is the Grid shell erection process. This process is time consuming, because it is necessary to erect the whole grid at one moment in gradual steps and keep it in the final position until final reinforcements are done.

During the first erection of the designed structure there were problems due to the chosen experimental process.

At first the completed timber grid was folded (squeezed), reinforced with perpendicularly laths fastened using zip ties for better manipulation of the grid and to get the grid safe without breakages to the starting position. After that the Grid was settled to the position in the pool and supported by horizontally fixed ladders.

After releasing, the grid was slowly spread out, which caused non symmetric force distributions (one part was situated on the flat grass surface and the other one was slacking inside the pool), because just three horizontal ladders were installed. The ladders were used afterwards also as a vertical supporting elements.

Fig. 6.3 Erecting procedure – lifting up, tightening with belts [by author 28.9.2015]

Fig. 6.4 Erecting procedure – Supported final shape anchoring [by author 28.9.2015]

This proved to be an in practical solution, because the grid in higher position which is „pierced“ with the ladder is not movable. As a result it is not possible to change the ground plan position easily. Another problem is a small contact surface with the supporting element which causes more breakages as compared to using flat-head elements. Doing some more attempts the whole grid was brought to the starting position and continued again next to the pool on the green grass surface.

Fig. 6.5 Erecting procedure – Supported and anchored final shape [by author 28.9.2015]

The other important thing is to spread out resp. shrink the grid into the right rhombic angle to prevent further necessity of changing it. Later on this is very difficult due to the shape, which is already bent.

This is a very important step, also the most demanding, time consuming and heavy on costs by using proper scaffolding, which has to be able to be dismantled after the whole structure is erected and fixed. When lifting up the whole grid during the first workshop many mistakes were made, which would not be even predictable without doing this experiment. It was really helpful to understand how the grid structure acts, especially in case we change one point of the grid, the whole grid changes.

By using a crane or another engine power lifting element much time can be saved, on the other hand all has to be well prepared and the points of lifting distributed in a sensible way to avoid material damages. Other significant advantage is the possibility to move and rotate the whole grid to reach required shape. In this experimental case there was the erection done by prepared long laths with shorter laths perpendicularly drilled to the end which creates „T“ shape. With such bars the whole grid was erected and at the same time two pieces of fastened straps secured horizontally. When the final ground floor plan was settled, lines sitting on the ground were anchored to the ground using rest pieces of timber.

After the final shape was reached all slacked screws in crossings were finally tightened. This should toughen the whole grid before next steps, supporting elements were still left on the positions.

- *Perimeter tightening*

After lifting up the grid to a sufficient height, tightening all screws and anchoring timber parts in contact with the ground, the periphery fixation needs to be done in the whole perimeter to fix the laths position so that they have no more chance to deviate from the given position.

When final shape is reached and the perimeter fixed, additional timber laths on the top from along the whole perimeter are necessary to be attached. In the case of the covering there were used additional three lines, which would be not sufficient for a real long-term structure.

For peripheral stiffen a second layer from the bottom may help a lot, because these structural parts are most strained.

Fig. 6.6 Final shape perimeter tightening [by author 28.9.2015]

This construction step helps a lot to represent the grid shell with highlighted perimeter lines and finally defines finished structure.

Fig. 6.7 Perimeter fixation [by author 29.9.2015]

Fig. 6.8 Finished grid shell structure [by author 29.9.2015]

7 Drawings

For more detailed analysis, the project of a grid shell cover in front of CTU was selected. It is the main project of four, which was processed during experimenting with grid shell full scale models.

Location: Prague, Capital city of Czech Republic

Fig. 7.1 Site location Prague 6 – Dejvice [https://www.google.cz/maps]

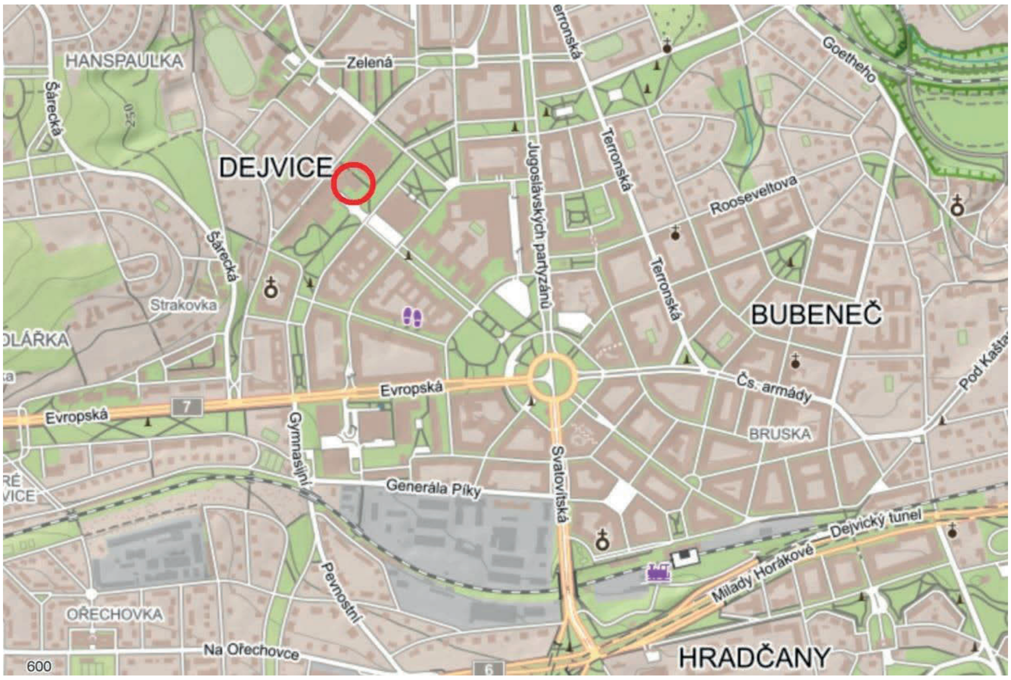

Fig. 7.2 Site location Prague 6 – Dejvice, Thákurova 2022/7 [https://www.google.cz/maps]

Drawings as an output from 2D and 3D comptuter design in specialized software (Photoshop, Corel Draw, AutoCAD, Rhinoceros, SketchUP

7.1 Site plan, Ground plan

Faculty of Civil Engineering in Prague in Czech Republic is on the aerial photograph represented by buildings A, B, C and D. All buildings are south-east oriented, which is consequence of the green zone passing through. This green „belt“ is breathing in more life and offers an pleasant crossing between students and people walking around. Very close to discussing area there is the main entrance to the National Technical Library with a restaurant on the corner. Along the green belt there are nice full-grown trees, completing fresh and cosy atmosphere.

The pool is divided into two differentially big parts with different heights and framed all around by three rows of concrete steps. This makes the pool very intended and variable for using as a free-time place or meeting point, it is comfortable to sit on high concrete blocks of dimensions 1,6 x 0,8 m.

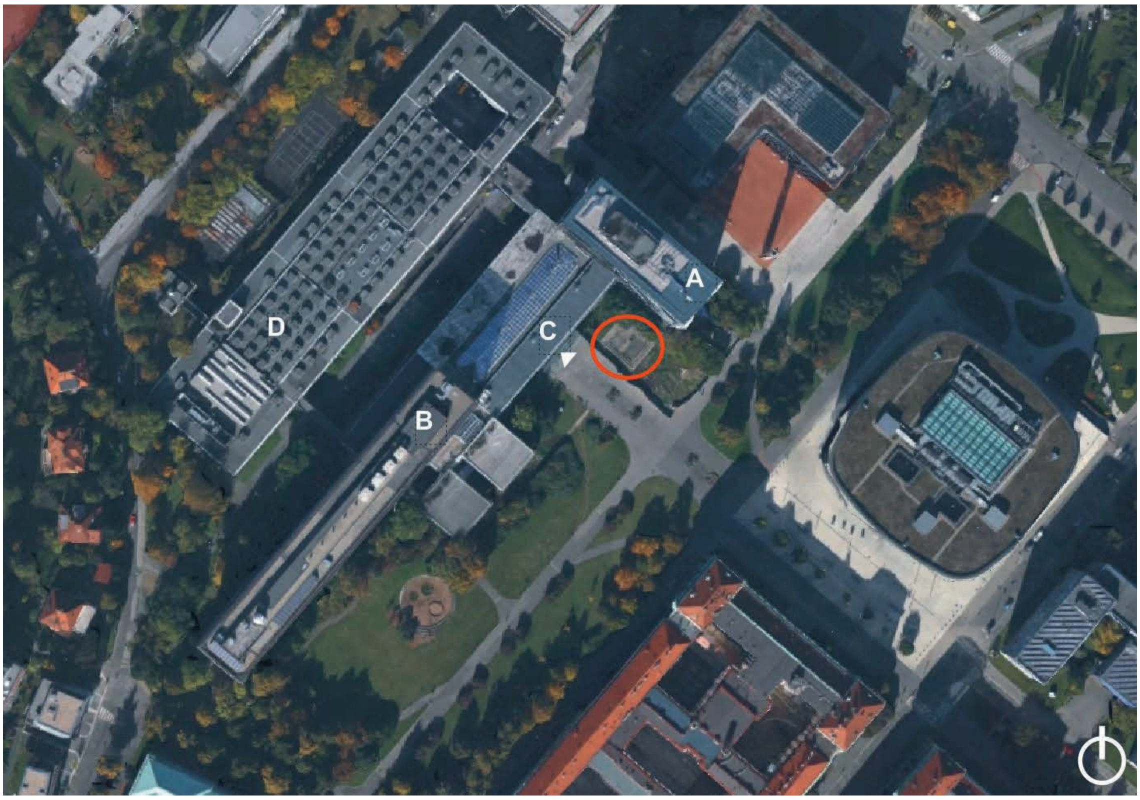

Fig. 7.3 Google map site view [https://www.google.cz/maps]

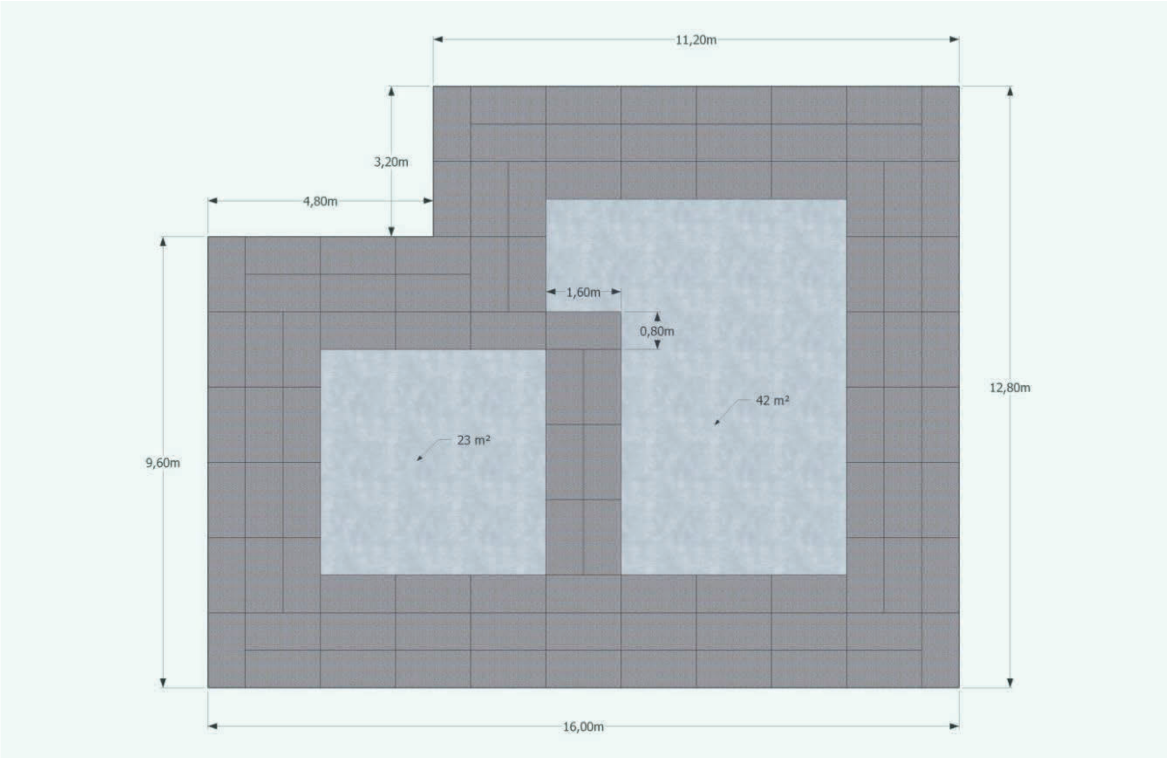

Fig. 7.4 Pool ground plan [by author]


Fig. 7.5 Pool photo [by author 20.6.2015]

7.2 Sections, orthogonal views

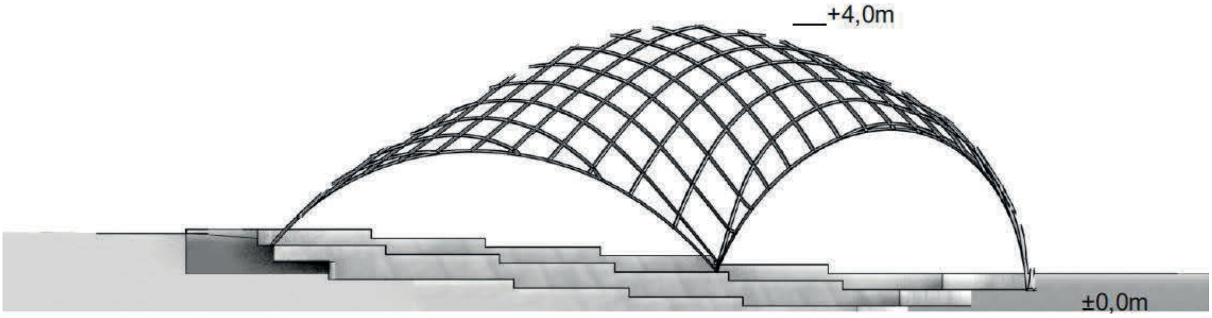

Fig. 7.6 Section view 1

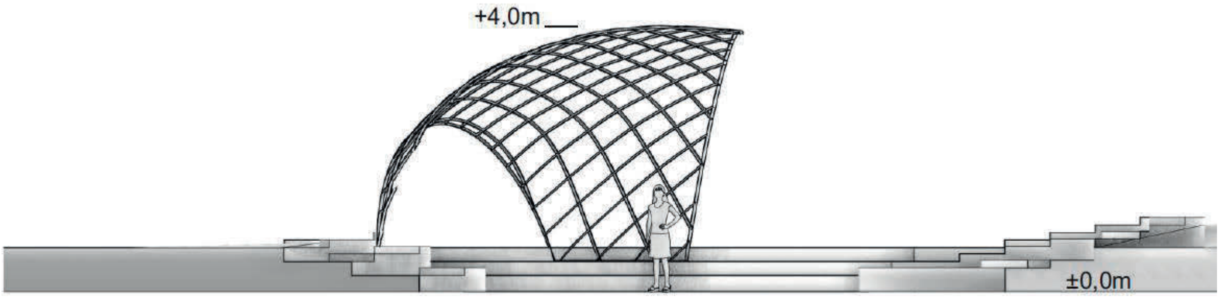

Fig. 7.7 Section view 2

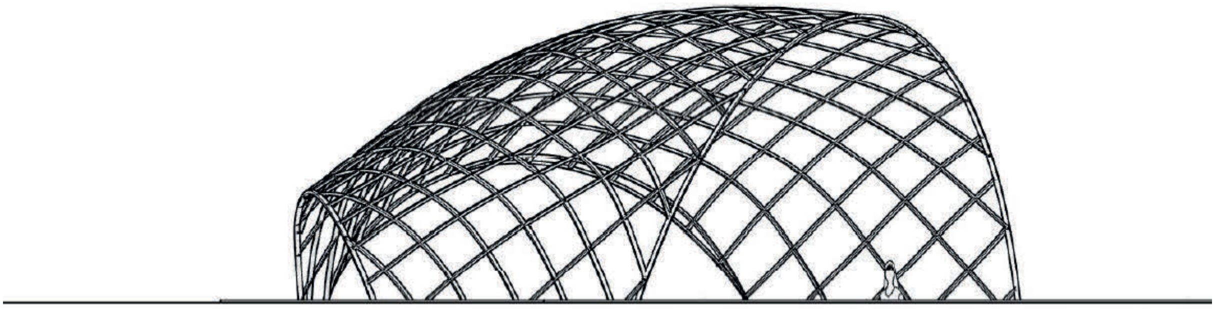

Fig. 7.8 Side view 1

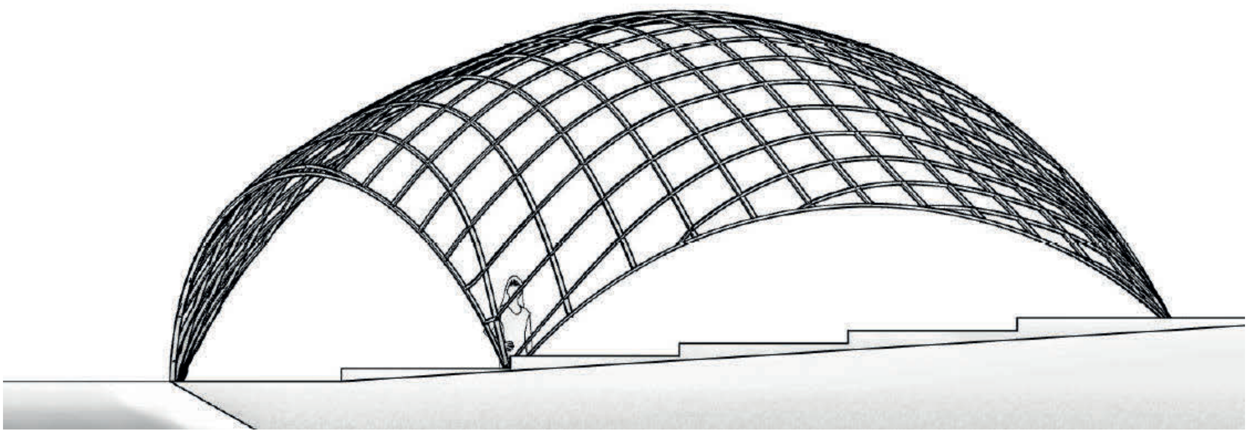

Fig. 7.9 Side view 2

7.3 Visualization, perspective views

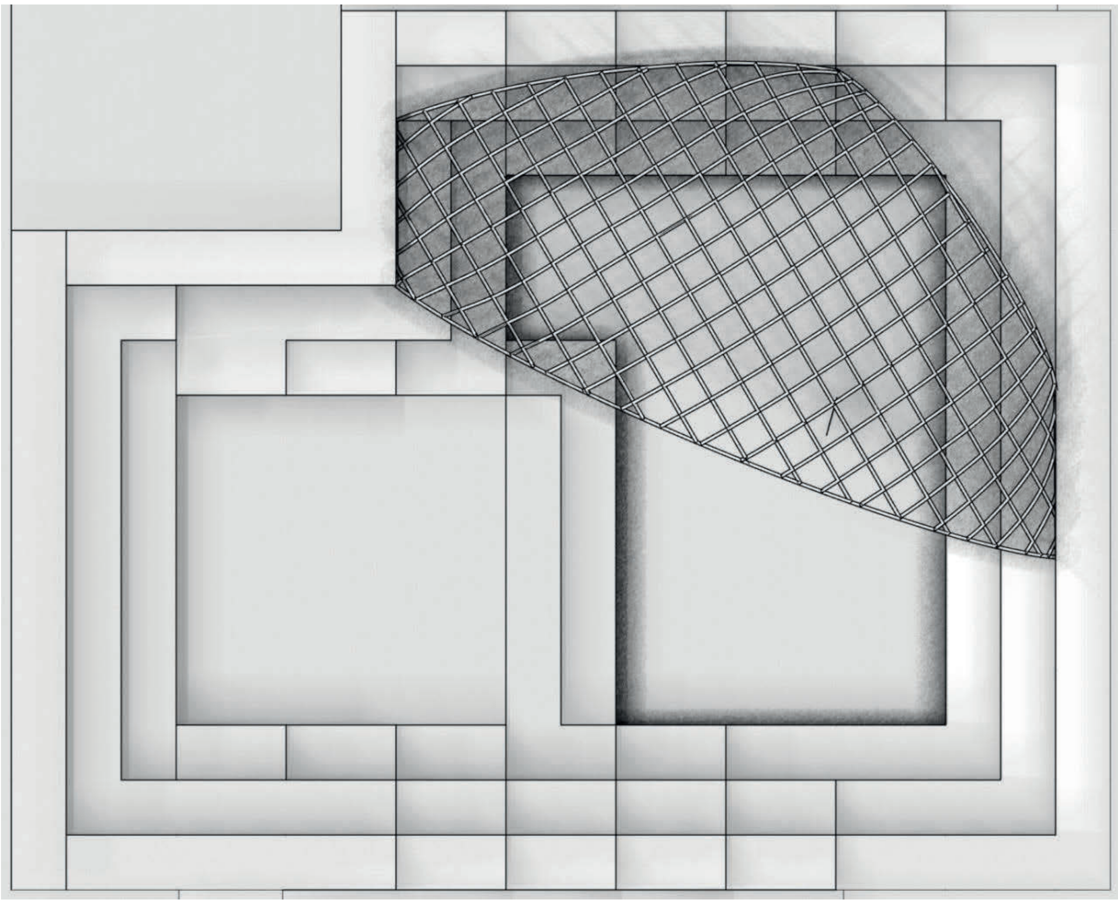

Fig. 7.10 Top view

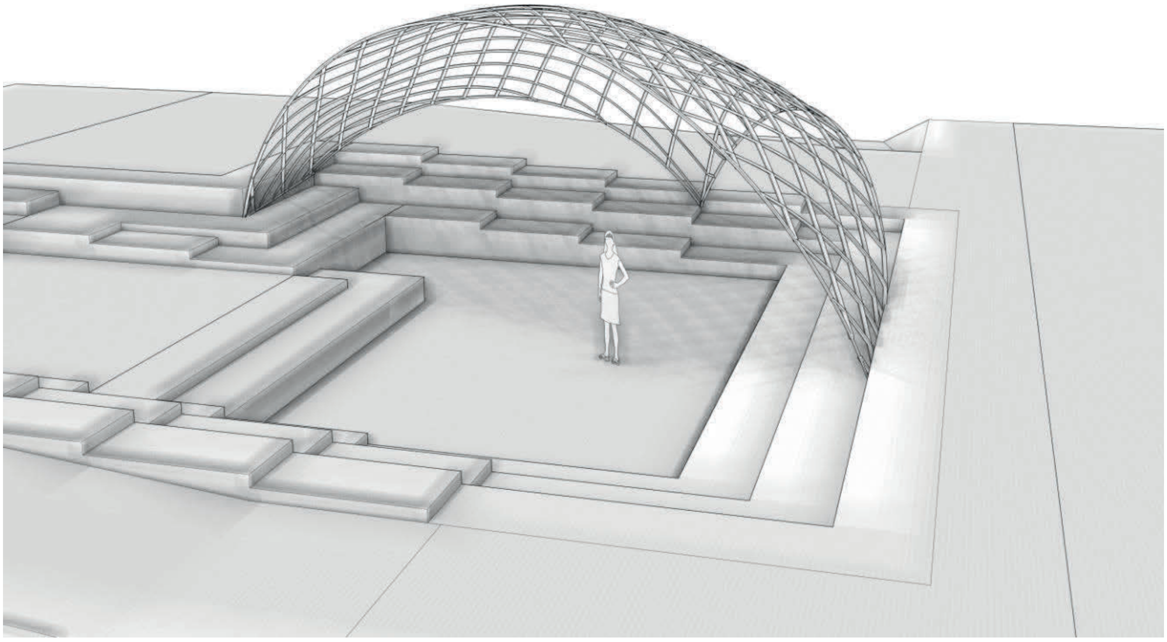
Fig. 7.11 Perspective view from the pool surrounding

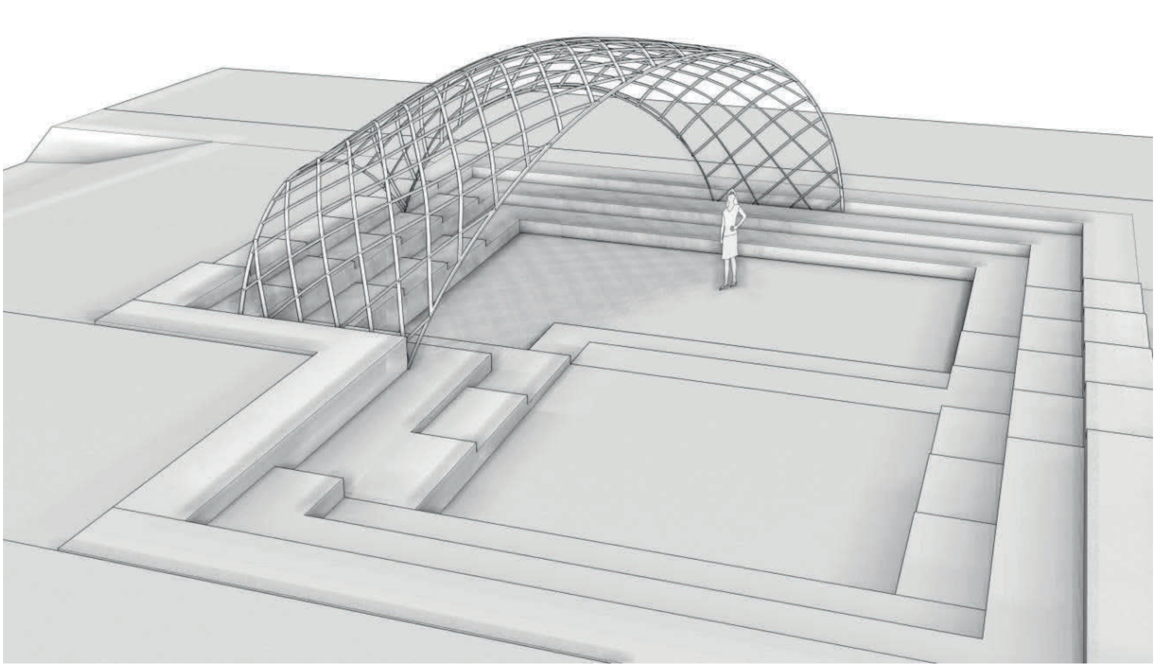
Fig. 7.12 Perspective view from the pool surrounding

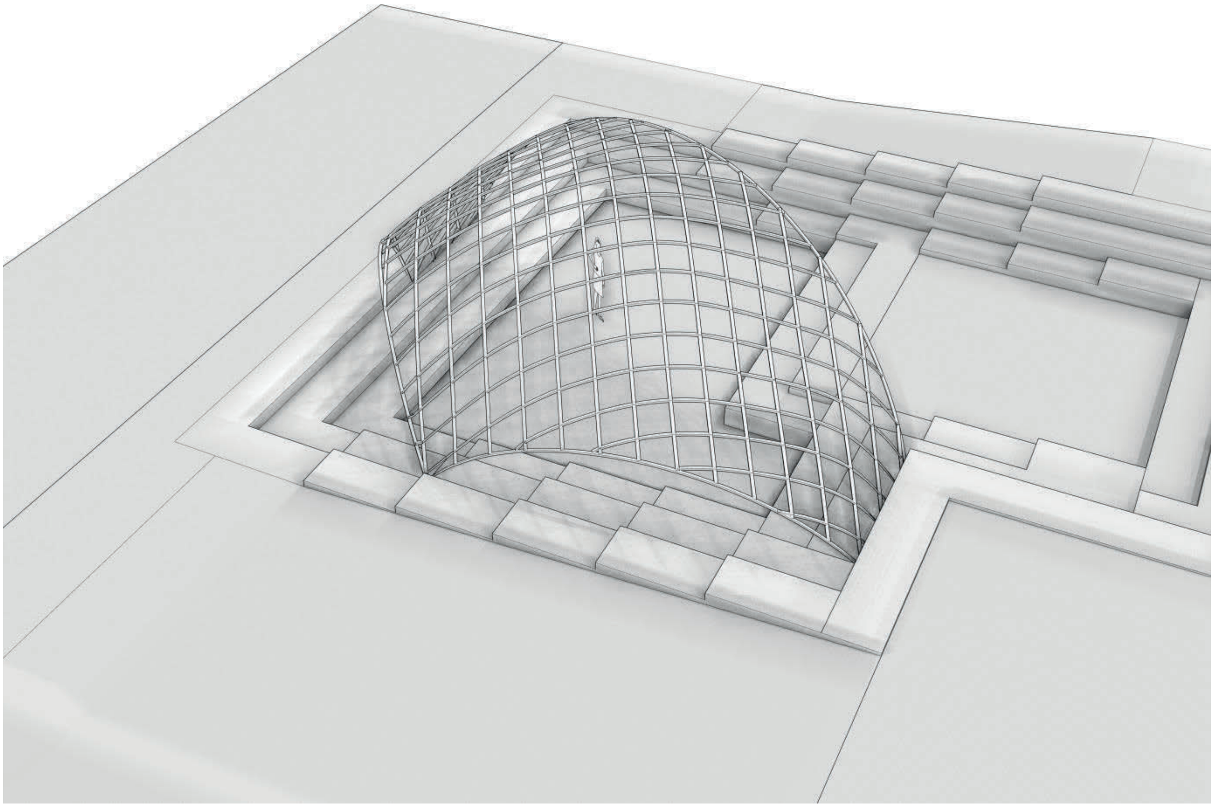

Fig. 7.13 Bird view

8 Photo documentation

All used images were made by author during the whole procedure of the grid shell designing, assembling, erecting, fixing and anchoring. There was also a picture shot taken in the sequence of 5 seconds to demonstrate the structure erection with all connected difficulties and problems, which will serve as a groundwork for next grid shell student workshop and past realizations.

8.1 Photo of final prototype condition

Fig. 8.1 Finished grid shell structure, south-west view [by author]

Fig. 8.2 Finished grid shell structure, east view [by author]

Fig. 8.3 Finished grid shell structure, north-west view [by author]

Fig. 8.4 Finished grid shell structure, west view [by author]

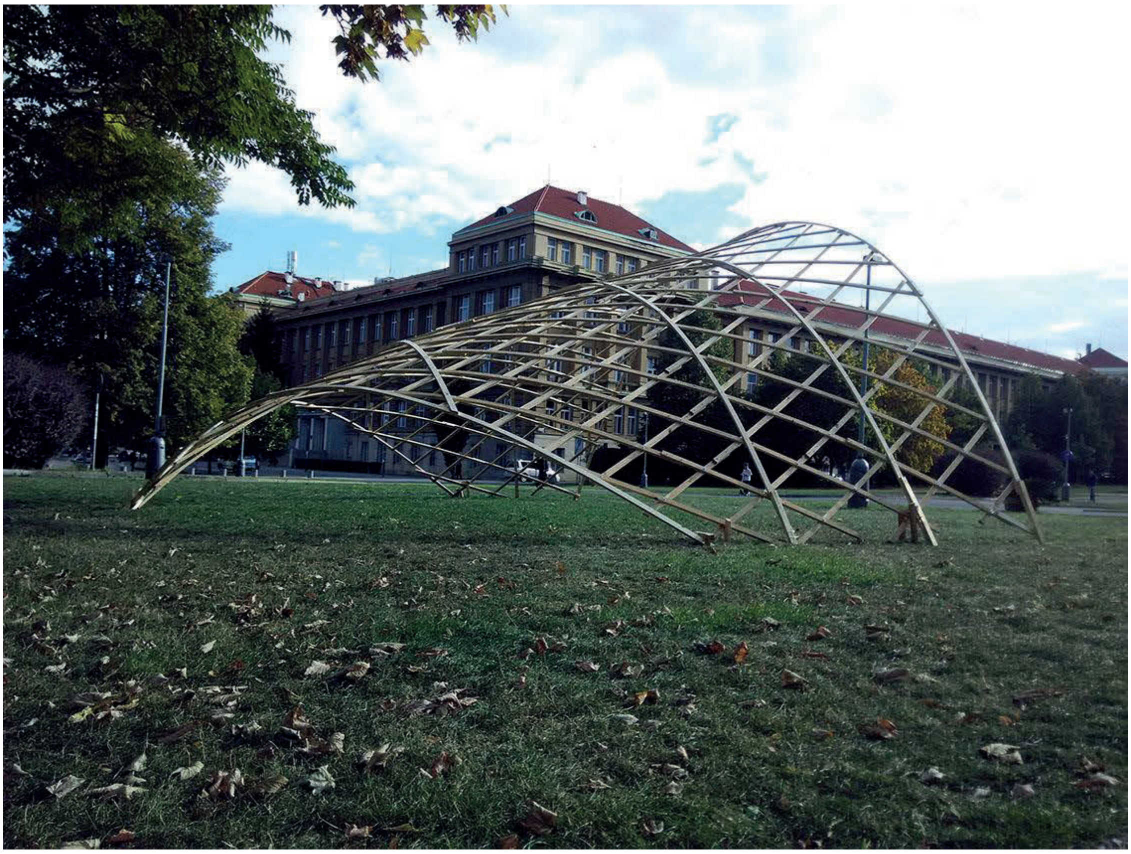

Fig. 8.5 Finished grid shell structure, northern view [by author]

8.2 Photo of physical model

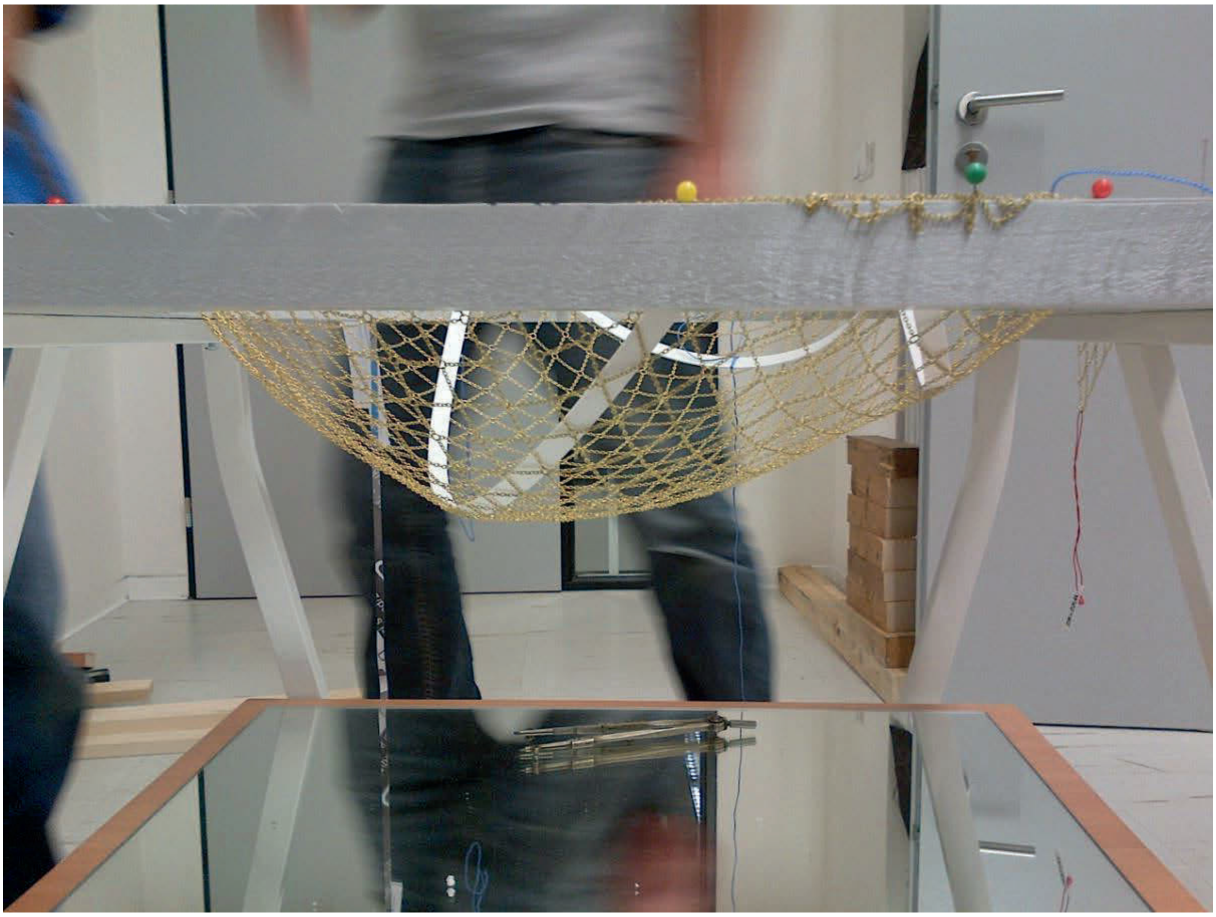

Fig. 8.6 2nd workshop - hanging chain physical model [by author]

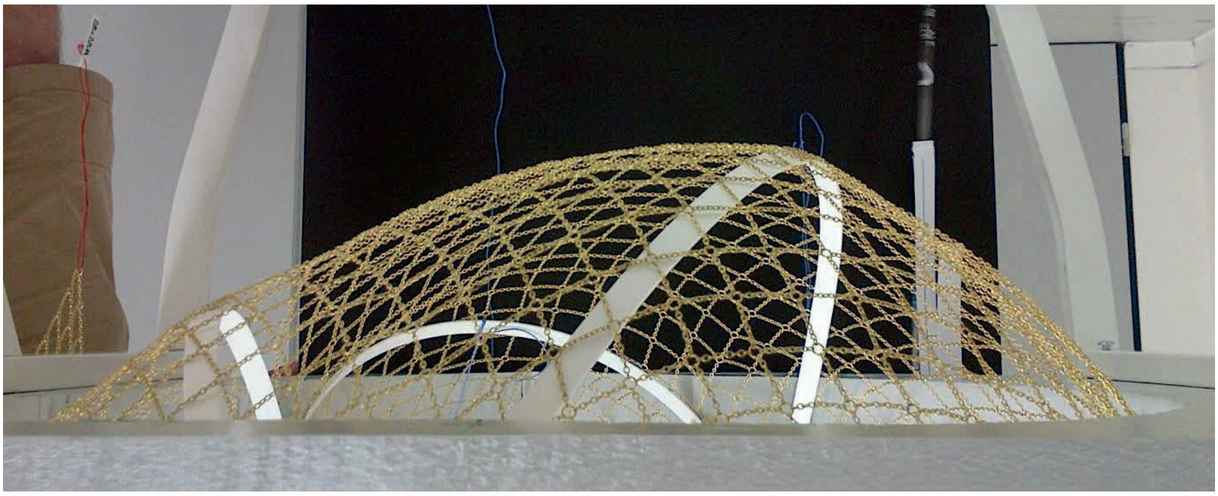

Fig. 8.7 2nd workshop - hanging chain physical model, inverted [by author]

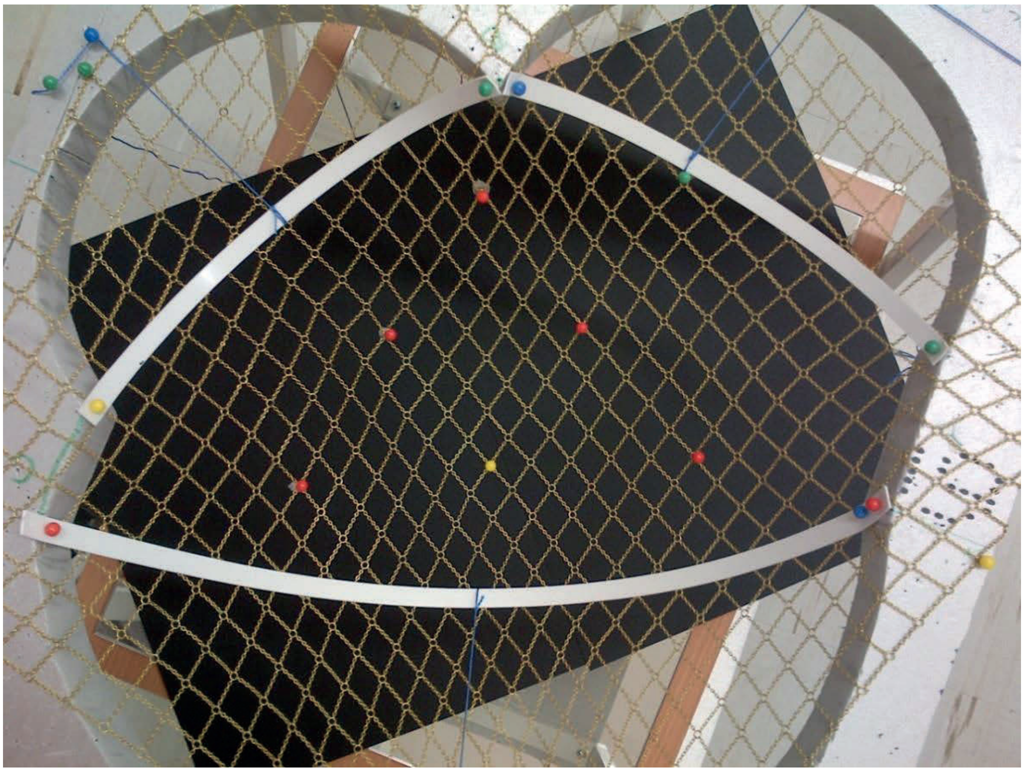

Fig. 8.8 Hanging chain physical model workflow

different rhombus angles by form finding [by author]

9 Conclusion

The goal of this Master Thesis was to create a feasible design of a grid shell structure and to build up a structure while understand the issues of building this more than interesting project itself. As a starting point there was a first workshop organized in cooperation with students and friends. Many different materials were used for the physical modeling and the very first grid was assembled.

This workshop became very valuable source for answering many questions, where I would highlight few to gain the idea of its virtue how to erect. Above all, when we bend a grid even in one curvature it wants to straighten to the starting flat position.

In the specific case of first small structure (simple sitting covering in the entrance atrium of CTU) there must have been the anchoring done forcibly by using 4 mm wires. The shape must be designed precisely and in case of generally larger meshes. They are easier to bend in double curvature because of the bending limits due to cross-section capacity. In case of timber it means that as small structure we want to build, as thin cross-section we should use. This phenomenon causes some difficulties within connections of these elements.

The second workshop arose many additional obstacles belonged to issues we came across, primarily connected with bigger scale of the structure. The major problem we had to deal with and find a solution was to design the whole assembly of the grid on the site where was the erection process realized. This was the most important step in the whole procedure.

The timber grid perform very unpredictably and it is sensitive on every little force involved. The erecting procedure must be well organized and every participant must provide each planned step perfectly to avoid breakdown or collapse of the structure in the worst case. The number of people involved in this project is rather to be limited to be able to cope well with the workflow.

The result was successful from my personal point of view and it had many positive reactions. As a crucial judgement of this project is that it met the expectations of the authorities of the CTU, who agreed on the realization in spring 2016 from larch timber and single-layer membrane covering.

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List of Figures

8.8 Hanging chain model workflow, different rhombus angles by form finding [by author]

Used software

Rhinoceros 5.0

AutoCAD

SketchUp

Photoshop

Corel Draw

Microsoft Excel