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HUMPED SURFACES
Reflections on a traditional high point design for membrane lightweight structures

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

supervised by
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Basel, 23.11.2018

Affidavit

I, STEPHAN HELMUT TÖNGI, hereby declare

1. that I am the sole author of the present Master's Thesis, "HUMPED SURFACES", 116 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, 23.11.2018

Signature

Acknowledgements

Mother † Thank you for your love. You raised us with your spirit of optimism and this distinctive sense of humour. Thank you for always inspiring me with confidence.

Thank you Annette, my beloved wife, for giving me love and time and forever encouraging me.

Thanks to my beautiful children Vera, Gilles, Gina and Livia for being patient with Daddy. I had so much less time for your young lives; instead you were never tired of answering the great many of my questions as a scholar.

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I am deeply beholden to Martin Siegrist for his unremitting commitment to help me set up a running system for computational formfinding during countless days and nights of work with all his expertise and enthusiasm.

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Thank you father, my brothers and my sister, for supporting me.

Thank you Rolf Furrer my friend for your inspiration. Your unconventional mind-set as an architect is a true model.

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Abstract

The present work is focussing on a basic category of membrane lightweight structures. The humped tents or humped surfaces. “Humping up” a fabric is one of the most elementary measures to add double curvature hence to increase pre-stress in a tensile structure like a tent, an awning or in modern terms a membrane lightweight structure. Even if not finally documented, this supporting system was presumably developed thousands of years ago by the nomadic tribes of the Middle East and has kept dominating black tent architecture until today. In the early days of Frei Otto’s work, several pavilions were developed as humped tents. The humped tent henceforth should be considered as one basic form of peak tent within the whole typology of membrane lightweight structure shapes. Nonetheless the concept has sparsely been used in bigger or more recent projects. Accordingly documents are scarce and hard to find. Humped tents are an underestimated species in the field of tensile architecture. Without any doubt humped surfaces are worth a deeper exploration and merit more attention in the building industry. The aim of this research is to give the reader an overview of the subject covering the history, the nature of such structures, the architectural potential and the technical challenges. Furthermore it is the author’s key intent to introduce proprietary design strategies. Newly invented techniques and refinements for traditional formfinding i.e. physical modelling, along with specifically developed computational simulation i.e. numerical formfinding are the pivotal contributions to an improved work flow in the design of humped membrane lightweight structures. This work represents an attempt to properly examine humped surfaces in tensile architecture and close a gap in the available means of labour.

Table of Contents

1. Introduction

The reason for starting a research on this topic was not an arbitrary decision.

Early during the master course at CEC, TU Vienna, the discovery of the aesthetic affluence set the course for considerations about the architectural and technical potential in humping up a membrane.

A spontaneous idea to build a full-scale humped tent as a research project was intriguing even though was dismissed due to the lack of knowledge at the time. While revisiting the lectures files, the home works and sketches however; the subject emerged to be important enough, as to call for a proper examination.

A first case study on a membrane structure dealt with a building in Switzerland, which can be described as a typical humped surface. Unlike most of the well-known structures there was something special about this shape that made it so interesting.

Figure 1: VonRoll Pavilion, Oensingen, Switzerland

The formal aspects of a surprising geometry on the one hand and quite a few technical secrets on the other determined the project worth taking a closer look.

Within the case presentation, this building was mistakenly classified as a “hybrid membrane structure”.

Jürgen Hennicke rectified this by introducing the term of humped tents to the audience, referring to the classic supporting system of that central highpoint.

On Nov. 29. 2013 at the TU Vienna during Unit 1 of the CEC master course program regarding membrane lightweight structures Jürgen Hennicke again was conducting a lecture on physical modelling. The students were shown how to create stocking models to explore the various types of shapes in order to get a preliminary visual impression of a design idea.

All sorts of results could be seen from the student's work. Most of the models came out as standard high and low point shapes that resulted from tearing material up and down and back and forth. Personally, I was mesmerized by the stunning simplicity and the exiting effect of humping up the knit fabric with a styrofoam ball on top of a wooden spit.

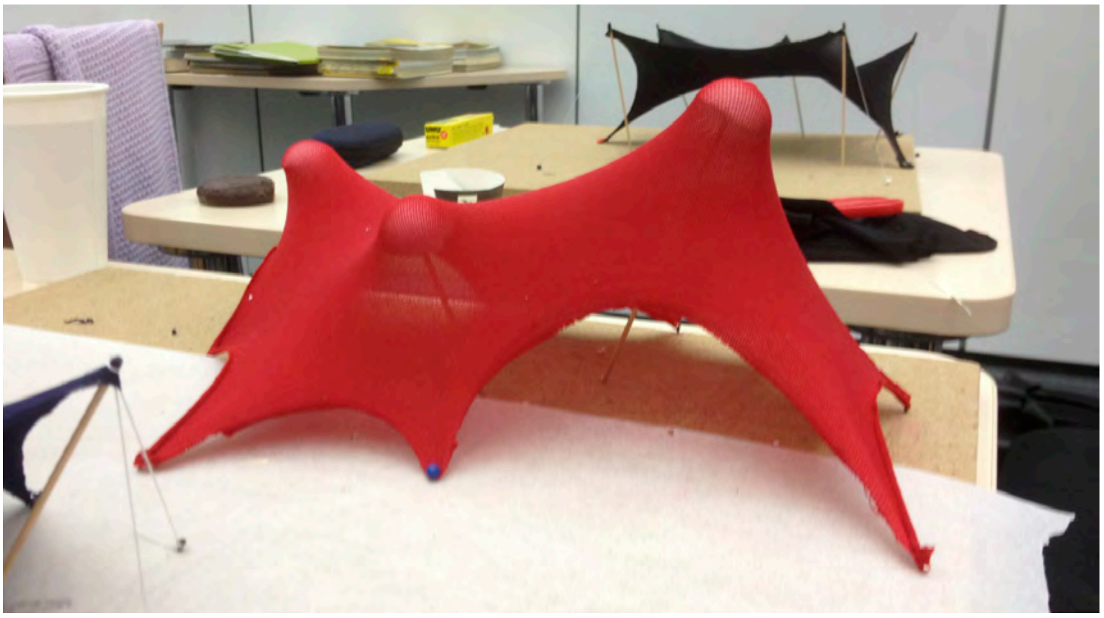

Figure 2: Stocking model, Vienna Nov. 2013

Looking back to the process of choosing a subject for a master's thesis this lecture was crucial. Eventually the topic of humped surfaces emerged as being the core field of interest more than any other.

Although the master course comprised classes on a huge variety of topics, none of them ever really focussed on this rare species of tents. Moreover, it seemed to be impossible to find any software tool, which featured the abilities to model or even calculate this sort of shapes. Even worse was the advise on the subject from the expert engineers and tent builders. State-of-the-art in building a humped surface seemed to be a shifted approach in the form finding process and an even more tinkered one in the way of making. All in all this was a very unsatisfying situation.

Humped tents are a rare design species in contemporary tensile architecture.

Thorough inquiry has given the impression that these shapes have been abandoned for a longer period of time and therefore have suffered from little development over the past decades. While being an important study subject in the early works of Frei Otto and his associates followed by a considerable number of beautiful buildings dating to the nineteen-fifties, the humped tent has become a neglected niche in the younger history of membrane lightweight structures.

There is far more potential in tensile architecture for these types of structures by virtue of their aesthetic appeal, the over all architectural value and definite technical advantages.

A general lack of tools, hence resulting obstacles for the design and engineering of projects may be one major reason for the limited number of existing buildings.

Presumably humped surfaces would be much more part of architectural consideration if they were more accessible for the modern planning process. This includes all steps from form finding via engineering to a final realization.

As a consequence of the poor basics this thesis attempts to provide a better comprehension of the nature of humped tents and makes a proposal for the workflow with reference to developing and designing new projects.

2. Objective & Methods

<u>Objective</u>

As stated before the aim of this thesis is to deliver a profound understanding of the nature and behaviour of humped surfaces in membrane lightweight structures i.e. tensile architecture.

Furthermore, the major goal is to improve the workflow of projecting and designing humped tents by proposing methods for both physical and digital modelling in the form finding phase of new projects.

<u>Methods</u>

Two different methods are required to accomplish the above-mentioned goals.

Firstly a general understanding of the subject and it's theoretical fundamentals is pursued by highlighting the historical background, by summing up the literature on the early work of Frei Otto and associates and by deepening the information via adding a selected number of case studies.

Secondly the practical aspects and the introduction of new tools for an improved design strategy will be taken into account. A detailed report on both traditional analogue and modern computational methods used in the course of my preliminary experimental stage will document how far the new working aids have grown in the meantime.

The former being an optimized way of rapid and accurate physical modelling the latter consisting in a digital form finding tool based on the popular Rhino3D® computer aided design application utilizing the Grasshopper® plug-in. The Grasshopper® visual programming environment for Rhino3D®, is a node based editor for graphic algorithmic modelling. Within the research aim of this thesis a proprietary definition was written to create geometry and route mesh relaxation in the course of form finding iterations.

3. Historical Background

Several stages of tent making history need to highlighted in order to illustrate the provenience and point out the importance of the humped tent as an elementary highpoint design.

3.1. The roots

Humping up a tent cloth has always been a measure to create room and, maybe even more important, to increase the prestress in order to prevent the fabric from ponding. This logic can be observed in many traditional tents through all ages and continents.

From a historical point of view it is likely that humped tents in general have their origin in the tents of the nomadic tribes of Northern Africa. Even if not established, there is vast evidence due to the well-documented tent making tradition in the area of Northern Africa and the Middle East.

Moreover a considerable number of nomads still stick to their traditional way of life by using the tribal tents as a dwelling for the sometimes-extended families to allow for the study of them.

> *" (Hatton, 1979)and hunters. These tents are feats of engineering, having been perfected to totally support the nomadic way of life and provide complete protection from most severe environmental extremes. The women, who are in complete charge of the household, design, construct, pitch, and strike them. Various styles of nomadic tents have been used since ancient times." (Hatton, 1979: 61)*

The use of poles and stems is the basic supporting system "black tents". These elements exist in various types yet always create that typical humped highpoint on top of the tent roof.

Several types and sub types of nomadic black tents have been described in literature in accordance with the particular tribe and area.

On this subject an excellent book entitled "Architecture of the nomads", was written by Torvald Faegre, and published by John Murray in 1979. Torvald Faegre has gathered an outstanding amount of information on the nomadic tent making traditions all around the globe.

“The black tent is the tent of the Bible, the Jews, and the Arabs, and a hundred other tribes scattered over Africa and Asia. Its mark upon these people cannot be reckoned. 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. These people were probably only semi nomadic and tilled the soil part of the time. They moved their belongings on 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.” (Faegre, 1979: 9)

From a technical point of view most black tents are made in a similar way. Basically, sewing together a number of breadths assembles a straight tent cloth. A number of lateral tension bands and a larger central band reinforce the cloth and take the guying ropes. A central pole with a ridgepole on top is used to hump up the tent and create room. The same principle is found in most Bedouin and Berber tents around Northern Africa. Variations in detailing, size and order are numerous and define the various tribal traditions.

The mechanics behind the deformation of the originally flat cloth lays within the elasticity respectively the flexibility of the plain-woven woollen yarns. Woven fabrics are organised in warp and weft strands. By nature these fabrics have a considerable capacity of angular displacement and in the case of natural fibres like wool, a high elongation under stress is quite normal.

For illustration purposes the figures of the following pages are taken from Torvald Faegre’s book "Architecture of the nomads", since his beautiful drawings show in detail the mechanism of a Moroccan Berber Tent.

Materials for the cloth of a Berber Tents are woven goat or sheep wool, sometimes also cheaper palm fibres. The maintenance of a tent is a constant process of renewal, the lifecycle of a woollen cloth is scarcely exceeding five years.

Nomadic tents are still in use as dwelling for the tribes, which adhere to the traditional life style. Yet in modern times a growing tourism industry at least around Morocco and Tunisia is falling back to the Berber tent. Camel rides or caravanning is an extremely popular way to explore the desert. The hostelry of course uses the tent as housing to accommodate the guests, since it provides a lot of "tribal chic".

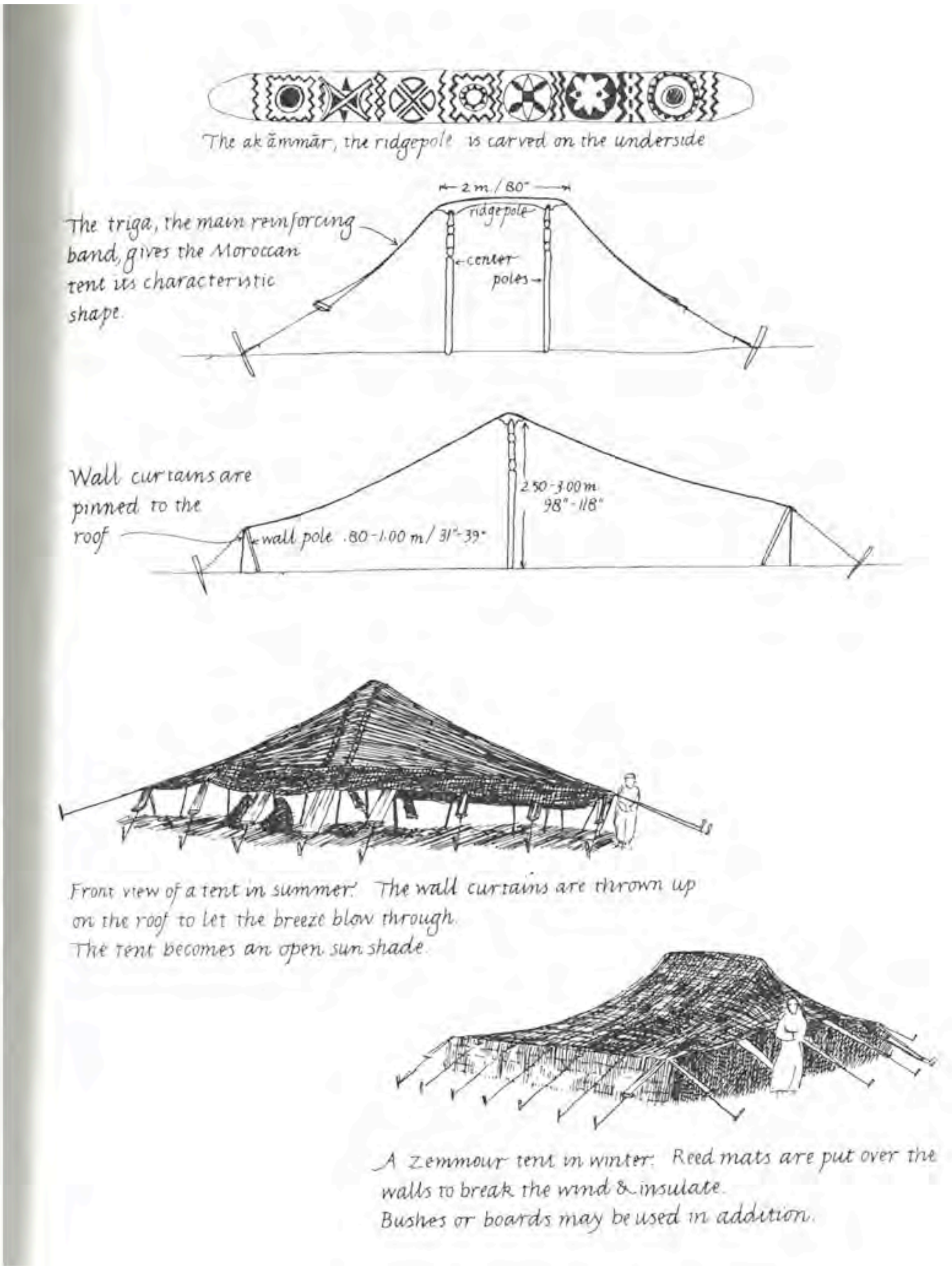

Figure 3: Basic shape of a Moroccan Berber Tent

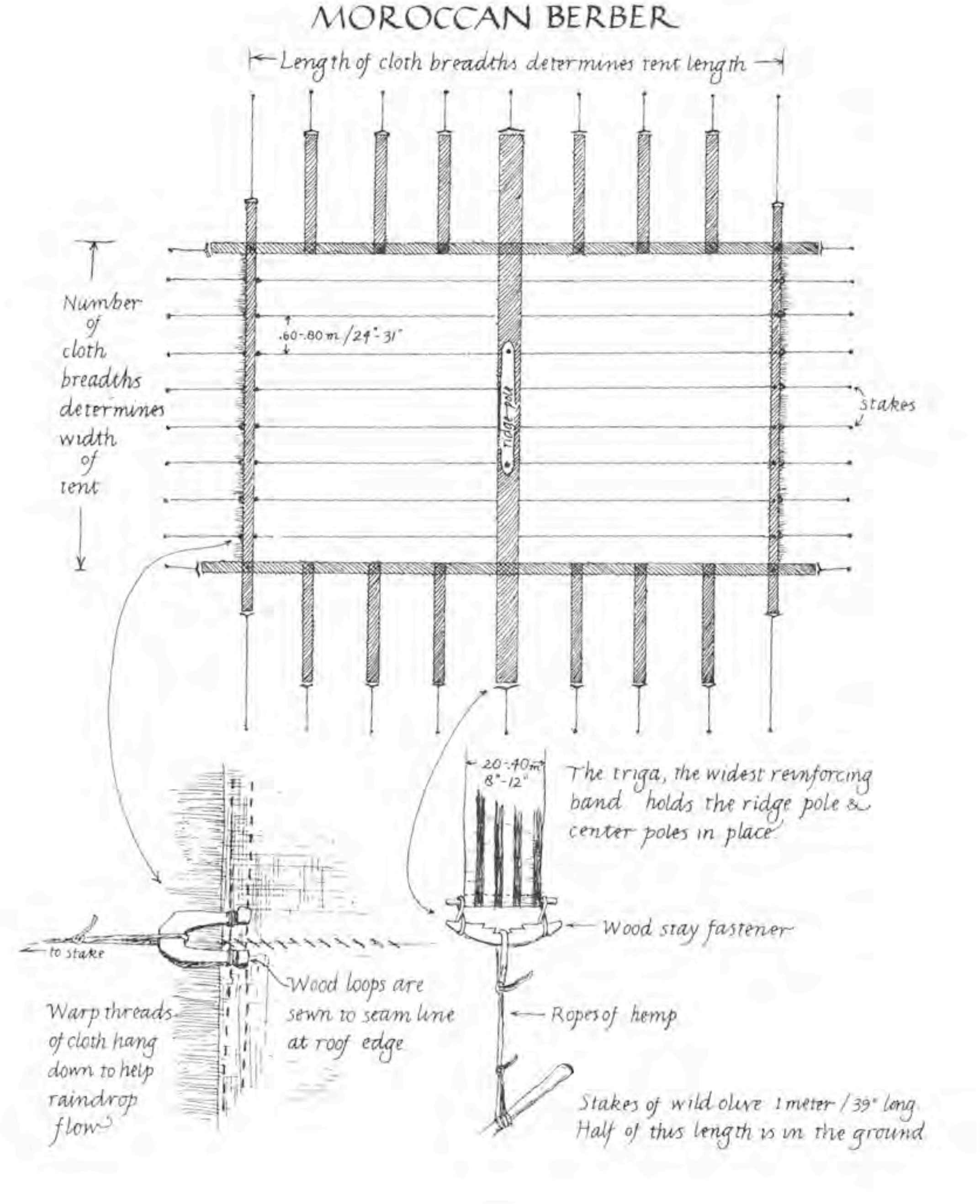

Figure 4: Moroccan Berber tent details

Figure 5: Tourist Camp in Tunisia, „breakfast“

3.2. From vernacular to modern building

Similar to black tents but far less sophisticated successors of the latter are, ancient world or medieval market awnings. A number of blunt wooden poles to carry a fabric represent a frequent concept to create a basic shelter that typically comes with humps in the centre of the roof and stretched out corners around the edge. Once again the simplicity of the measure speaks for itself. Changing the form (by inducing double curvature) increases the prestress of the fabric and thus stiffens the tent roof.

Figure 6: Medieval market awning replica

The basic and generally fairly flat humped tents are by no means to be confused with the far better known pyramid tents. From the Roman Empire throughout the middle ages until modern times a great variety of pyramid tents is known.

Figure 7: Medieval war tent replicas

The one or two or multiple mast tents represent a simple yet more elaborate shape and have been ever since popular as well as for military and prestigious purposes. The most refined specimen of course is culminating in the chapiteau tent, better known as big top.

Compared to humped tents, these more accentuated shapes require a decided cutting pattern to create pyramids, ridges and cones, while the former can take shape only by the pressure onto the supporting element.

Figure 8: Chapiteau "Das Zelt", Switzerland

3.3. The 20th century

Nowadays business is keen in accessing new fields and shows to be agile in satisfying the needs of an ever-growing market of leisure industries. Tents and awnings represent a core feature in the event business. Festivities preferably require temporary facilities. During warm the seasons a shelter is designed to protect parties and dinners from rain or wind. The stretch tent, e.g. a particular species of a humped tent has come up only a couple of years ago. These tents have become very popular since they are easy to pitch and also available in whatever shape and size. Their cloth is almost isotropic, resembling a neoprene suit or a rubber skin. Hence a rather pointed ram can be used to lift the fabric without puncturing it. In addition, the fabric doesn't require a lot of prestress to create shape in order to be held in place, which allows for simple foundation and guying.

Figure 9: Stretch Tent, Tentickle

3.4. Peter Stromeyer & Frei Otto

In modern tent making industry one company plays a key role not only due to it's position on the market but substantially in the development of tensile architecture so-called membrane lightweight structures.

The L. Stromeyer & Co. GmbH founded in 1872 in Romanshorn, Switzerland, was transferred one year later to Konstanz, Germany, in order to be present in the German market. Starting off as a tentmaker company, Stromeyer established the production of waterproof fabrics for military use after opening a weaving mill in

1878. The company soon gained a high reputation as a supplier for big tops and large tent structures in general.

After World War II the company was strongly inspired by the work of the young Frei Otto. Otto had been spending time at the Stromeyer factory as a trainee in order to gather tent-making skills while writing his dissertation. Being of a like-minded intent Peter Stromeyer and Frei Otto developed a close relationship. The tentmaker company henceforth escorted Otto on his path of developing tensile architecture and built most if not his entire structures until the seventies. Their collaboration was as remarkable as prosperous. Without any doubt the assistance of Stromeyer was one key factor to Otto's successful career.

> *"I was already working as an advisor for the tent company Stromeyer at the time. Stromeyer was the worldwide market leader in tent construction; it had built the largest tent halls for the Sängerfeste [Festivals of Singers] around 1900, as well as airplane hangars during the war.6 Most of my commissions went through Stromeyer, so I couldn't have complained about a lack of commissions. (…) The first four-point tent was erected for the Bundesgartenschau [Federal Horticultural Show] in Kassel in 1955—also the project for the open-air theatre in Stuttgart's Killesberg park. It was clear to Stromeyer that he just needed to turn to me and I would make a design for him. Whenever a commission came in, I was the obvious choice for him. That was very useful for me, especially since I'd written my dissertation on the subject of hanging roofs. I was Dr. Tent." (Otto, Ich war Dr. Zelt, 2013: 74)*

Even if this may sound all to self-confident, F.O. was full of gratitude and deep respect towards Peter Stromeyer. In the publication IL 16 Tents, 1976, F.O. dedicates the preface to Peter Stromeyer and held a laudation in honor of his person and his lifework.

Quite a few episodes narrated by F.O. in that same publication provide a good insight into the spirit of the Otto & Stromeyer collaboration of the late fifties. Most of the early projects at the time were realized exclusively via experimental approach. Trial and error along with countless tests was the method and a high time pressure was their daily business. The Stromeyer premises, the so-called Stromeyersdorf, in Konstanz, were the test grounds for real scale on site engineering. The environment with the manufacturing facilities enabled rapid prototyping and also made quick changes possible. A lot of the tents were successfully realised thanks to the company's know how which had been acquired in a purely empirical way.

Hence much of the fundamental understanding about tensile structures and their behaviour had to be caught up with in the course of subsequent examinations.

Nonetheless, Frei Otto’s output along with the assistance of Stromeyer was extraordinary. Particularly between 1955 till the late 1960s a considerable number of seminal projects was completed whereof most were novelties that became icons in the history of tensile architecture.

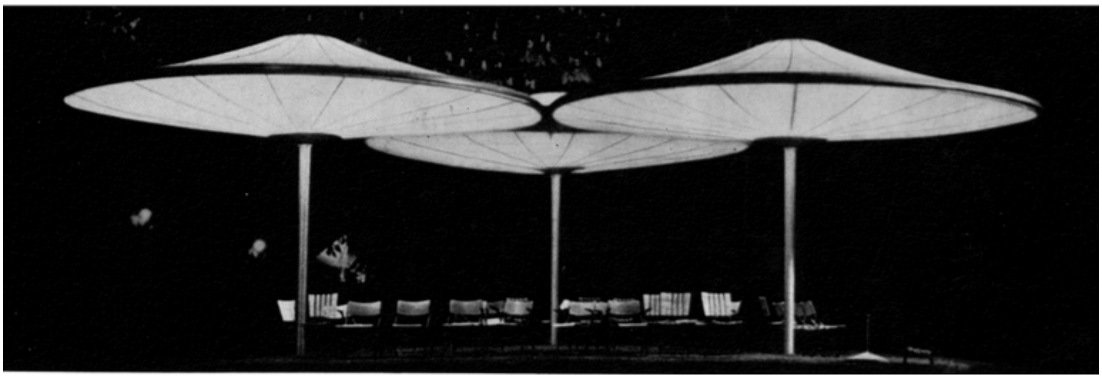

Figure 10 Three Mushrooms Kassel, 1955

3.5. Entwicklungsstätte für den Leichtbau EL

On a scientific basis Frei Otto firstly discussed humped surfaces within his dissertation “The Suspended Roof” in 1954. On page 18 he establishes a basic type of humped membrane consisting of a flat membrane inside a closed circular boundary with single punctual support in order to explain double curvature. However the term of humped surfaces or humped tents only occurs in association with the works of Frei Otto in Berlin.

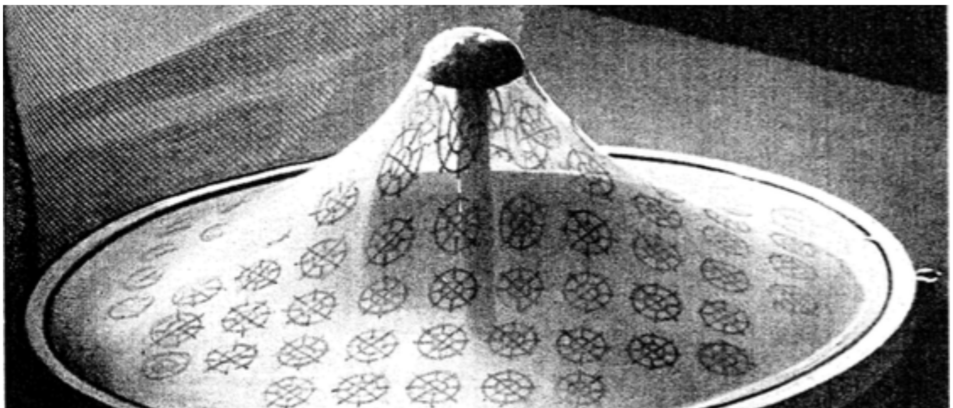

Figure 11: Double curvature, humped surface

After his studies at the Berlin Technical University, Frei Otto first began a private practice in 1952. In 1958, he founded the “Entwicklungsstätte für den Leichtbau”, Institute for the Development of Lightweight Construction called EL.

It was a private research institute in Berlin based in an ad hoc built pavilion.

The EL can be regarded as the predecessor of the Stuttgart IL, Institute for Lightweight Structures (Institut für Leichte Flächentragwerke), even if it was not yet an academic institution.

It is due to engineer and dean Fritz Leonhardt that F.O. was appointed to the Stuttgart Technical Academy in order to establish the IL.

Leonhardt met Otto earlier in 1954 after he had published his dissertation entitled "The Suspended Roof" (dt. "Das hängende Dach"). He largely agreed with Otto’s approach of using minimal resources for architectural tasks and presuming one optimal solution for every structural problem.

> *„Fritz Leonhardt war von Frei Ottos “unerschöpflicher Fantasie” so überzeugt, dass er sich als Dekan der Fakultät für Bauwesen der technischen Hochschule Stuttgart engagiert dafür einsetzte, Frei Otto nach Stuttgart zu holen. 1964 wurde Frei Otto nach Stuttgart berufen und das Institut für Leichte Flächentragwerke (IL) eingerichtet. Forschung-s und hochschulpolitisch ist es ein großer Verdienst Leonhardts als Dekan und Rektor, 1969 mit dem Sonderforschungsbereich (SFB) 64 “Weitgespannte Flächentragwerke” den ersten interfakultativen Sonderforschungsbereich an der Stuttgarter Architektur- und Bauingenieurfakultät begründet zu haben.“ (Weber, 2011, 175)*

Translation:

Fritz Leonhardt was convinced of Frei Otto’s “unlimited phantasy” so that he campaigned in his role as dean of the faculty for civil engineering for having Frei Otto come to the Technical University of Stuttgart. 1964 Frei Otto was appointed to Stuttgart and the institute for lightweight structures (IL) was established. It is the great merit of Fritz Leonhardt as dean and rector to have constituted the first interdisciplinary special research field (SFB) 64 “Wide span structures” in 1969 at the Stuttgart architecture and civil engineering department. (Weber, 2011)[1]

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[1] Translation by author with agreement by C. Weber

It may be misleading I term of chronology to talk about the EL and the IL here. Most of the projects and buildings that will be documented in the following chapter were planned and realized before the EL came into being.

The same must be said about humped tents since they were certainly not invented in the nineteen fifties, but Frei Otto and his associates did most of the fundamental research on these membrane structures in the Berlin days and as stated before in many cases retrospectively only. Meaning proper examination was undertaken after erecting or even past to dismantling. The EL literally represents the first institution to do systematic research in the field of membrane lightweight structures.

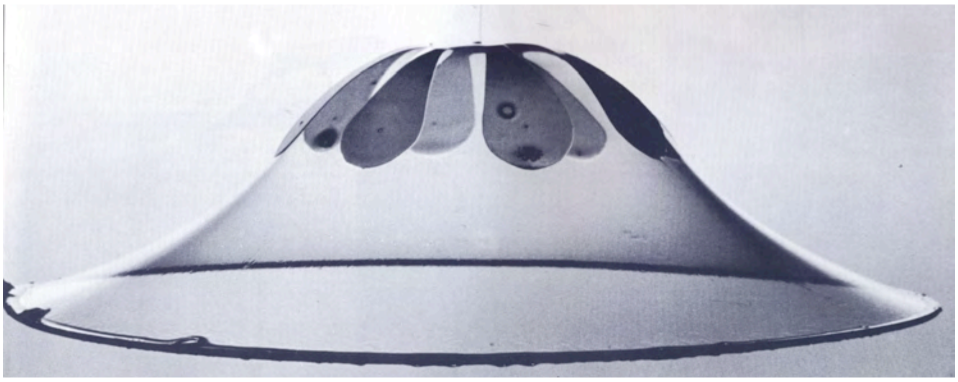
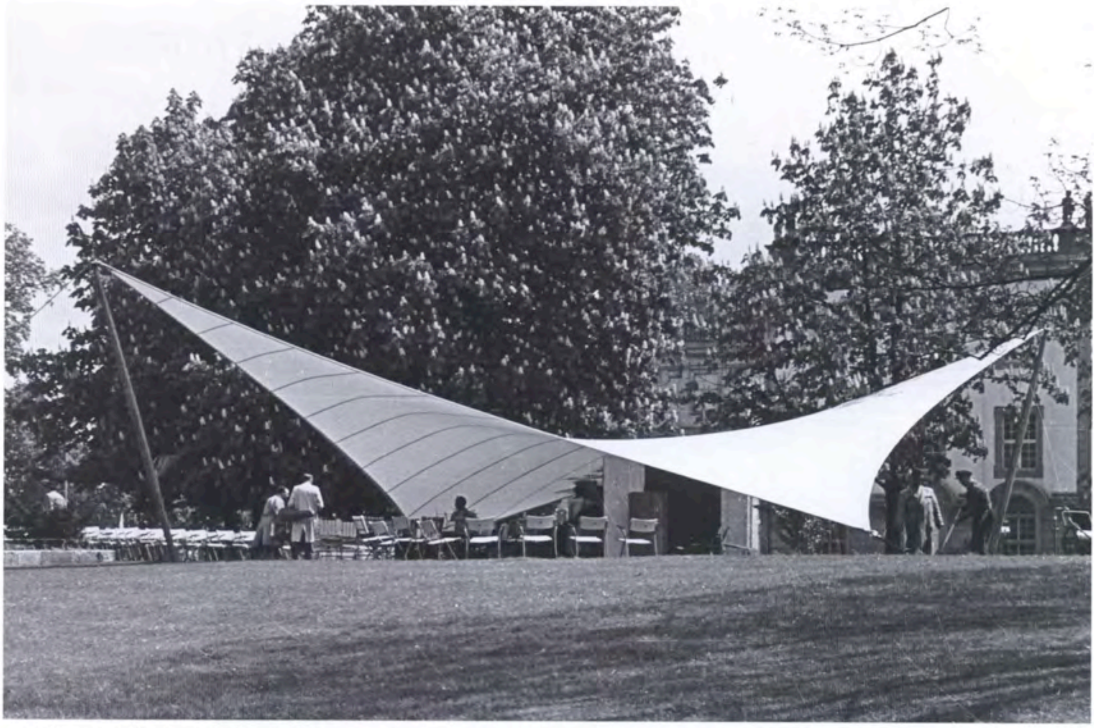


Figure 12: Soap film model of a humped surface

3.6. 1957


Federal Garden Exhibition Kassel 1955, music pavilion

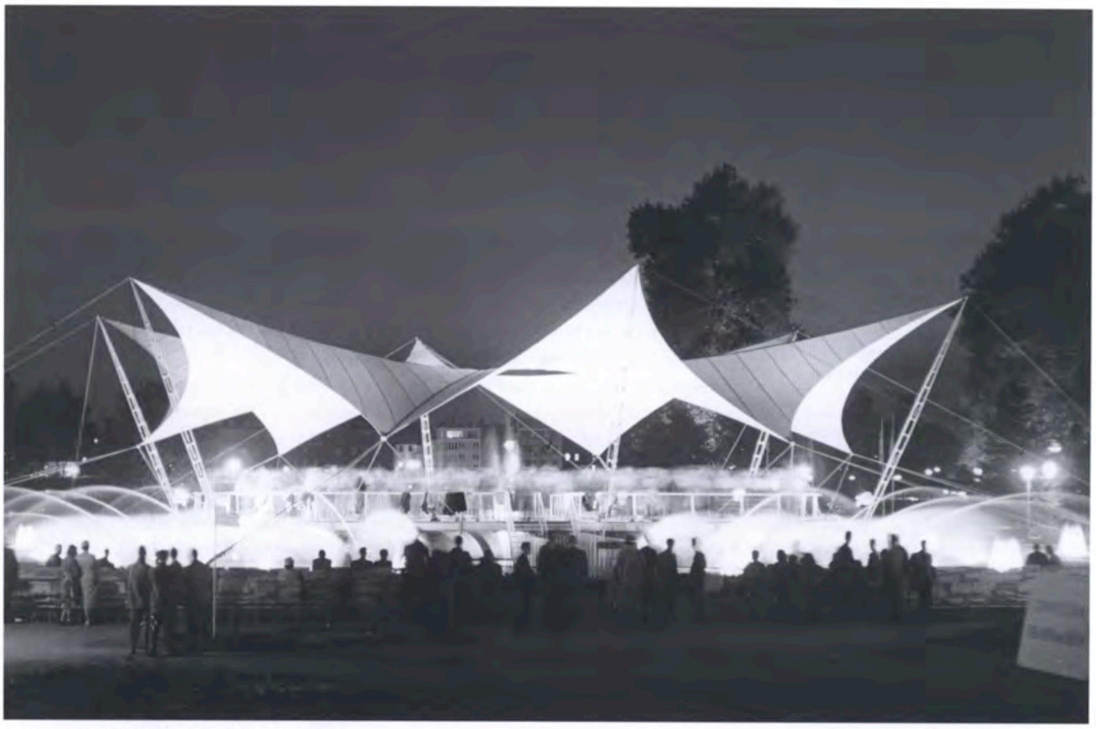

Federal Garden Exhibition Cologne 1957, dance pavilion

Figure 13: Music Pavillon Kassel 1955, Tanzbrunnen Cologne 1957

In 1957, the year before starting the EL, two important public fairs in Germany were scheduled.

One, the Federal Garden Exhibition was held at Cologne, the other, the INTERBAU Building Exhibition took place in Berlin.

Both exhibitions seemingly induced an important demand for awnings, tents and other lightweight structures to temporarily house the great many of exhibitions, give shelter to visitors or protect orchestras. Membrane structures were doing a good job at a reasonable price and were extremely fashionable due to their novelty.

Looking back to 1957 in a retrospective comment, Frei Otto would call this period the most dynamic of his whole career.

After the successful mandates for the 1955 Federal Garden Exhibition in Kassel, F.O. was given the opportunity to play a more prominent role for the Cologne show.

Otto invented some of the most iconic masterpieces in his oeuvre.

Together with Ewald Bubner, Siegfried Lohs and Dieter R. Frank, Otto built a series of four at that time experimental membrane structures. The best known among them being the outstanding "Tanzbrunnen" dance pavilion was a milestone in tensile architecture.

The stunning beauty of the wave tent deeply impressed the audience and certainly a lot of Frei Otto's reputation as an architect is rooted in this building.

However, the other tents where nothing less interesting and each of them worth to be mentioned since they all represent an archetype of tensile architecture.

3.6.1. Four Cologne tents

- Eingangsbogen – Entry Arch
- Tanzbrunnen – Star Wave Tent
- Spitzzelt – Peak Tent
- Buckelzelt – Humped Pavilion

But on the contrary the responsible committee of architects for the Berlin show seemed to ignore Frei Otto. He had applied in vain for an opportunity to demonstrate his achievements in lightweight construction in front of a larger public. It is conveyed that owing to a letter of protest to namesake Karl Otto, the responsible art director in charge, F.O. was finally offered to collaborate for the numerous tasks around the INTERBAU Exhibition. Accordingly F.O. together with his Cologne team was involved in the planning and the realisation of more than five structures, all of them being designed as humped surfaces.

3.6.2. Five INTERBAU structures

- Die Stadt von morgen – The city of tomorrow
- Sonderschauen – Special exhibitions
- Hauptrestaurant- Main restaurant
- Orchesterschutzdach – Orchestra canopy
- Café am Schloss Bellevue – Café Bellevue Castle

It is unknown to me why all the INTERBAU tents were conceived as humped tents. I can only make a few assumptions taking into account above all the circumstances of contract with the rigorous shortage of time on top.

- Humped tents are time saving in matters of engineering since little to no cutting pattern is required.
- The envelope for the two big exhibition halls was given due to a prior design decision to build the structure with MERO space frame girders.
- The giant surface area to be covered was an imperative for an economical solution.
- Two projects were spontaneously consigned to F.O. virtually as last minute orders

All these tents were presumably noticed a bit less by the grand public than the Cologne projects. Humped tents are by nature rather modest in appearance since they are less dramatic in shape compared to steep angled peak tents.

4. Case Studies

Within the scope of this paper the 1957 and later tents are regarded as key projects as such. The following case studies are meant to illustrate the bandwidth of this design and help to understand some of the mechanics behind as well as the technical problems that occurred during the period of use.

There are three criteria for the case selection:

1. The historical importance.

A criterion taking into accounts the context of a project within the oeuvre of F.O. Some projects have a particular economical background; others must be seen as highly experimental ventures with a considerable risk of failure.

2. Technical relevance.

The focus here is put on aspects of pioneering yet often-simple technology to achieve non state-of-the-art solutions.

3. Typological rank.

Features implying a position of a project within the narrower typology of humped tents.

4.1. “City of Tomorrow”, Berlin 1957

Architect:

Karl Otto, Günther Günschel 1956-1957

Design Roofing:

Frei Otto, Ewald Bubner, Siegfried Lohs, Dieter R. Frank 1957

Purpose:

Shelter for the international exhibition “City Of Tomorrow”

Dimensions and covered area:

52 m x 100 m, 4000 m^2

Fabric:

Polyurethane finished cotton

Features:

This exhibition hall consisted only of a roof and without any outer walls. The main bearing structure of the roof was a MERO space frame erected upon concrete columns. Karl Otto requested a lightweight and translucent cover for this exhibition hall.

F.O. suggested a truly simple solution:

> *"We screwed wooden slats onto the steel tubes, nailed the polyurethane coated cotton fabric on the raster of the MERO pipes and tensioned the membrane by humping it up with flexible wooden bars"(IL 16, 1976: 26)*

The fabric was arranged diagonally over the MERO structure in strips of 8m widths. Seams were glue welded by melting together the polyurethane coating under pressure.

79 humps formed a wave like landscape, which could only be overviewed from an elevated point of view i.e. from one of the surrounding buildings.

The ram to hump up the membrane in this case was a 3,2 m pine wood slat mounted on top of a steel strut which itself was equipped with an integrated spring to keep the prestress constant. The wooden slat took the rounded form of a braced bow under pressure hence it did not puncture the membrane. This strategy worked extremely well. However, the fabric showed much more relaxation than foreseen. During the installation time the deformation of the membrane considerably exceeded the planned amount. A figure for the degree of creep is not known but the difference is obvious when comparing the two drawings on figure 14. Nr. 9 showing the planned section, Nr. 10 illustrates the actual geometry after seven months of use. A more alarming problem occurred soon after erection. May 1957 turned out to be a very hot period. A service technician of Stromeyer reported to F.O. that the welded seams were dissolving as a reaction to the heat. Hence a two men team was engaged to constantly re-weld all the occurring breaks for the remaining time of the exhibition.

Observations:

The “City of Tomorrow” hall was a success. The concept revealed two major findings.

1. A big almost level surface of several thousand square meters can economically be covered with membrane.
2. A wind and waterproof surface is obtained by inducing prestress into the membrane via undulation i.e. by rhythmically humping up the fabric.

A similar concept was used for a number of smaller exhibition pavilions and also the INTERBAU restaurant. The smaller pavilions had sidewalls which were designed as humped surfaces. The INTERBAU restaurant had a covered patio on both sides of the main saloons. A pergola construction of square wooden frames on pillars was covered by membrane roofs to shade the patios. To tension the fabric a flying mast with a rounded head was installed to hump up the membrane. Flying masts are well known in architecture. They are described as a strut clamped between a bearing cable and a mortised member, generally representing a roof or a wall. This type of ram however is different from the supporting element on the big exhibition hall roof. It can be described as a leaf spring arrangement of wooden blades. The same concept was used in a refined way for the INTERBAU Café and later on for the so-called membrane halls. See also chapters 4.2 & 4.4.

Figure 14: Flying Mast Installation, INTERBAU restaurant

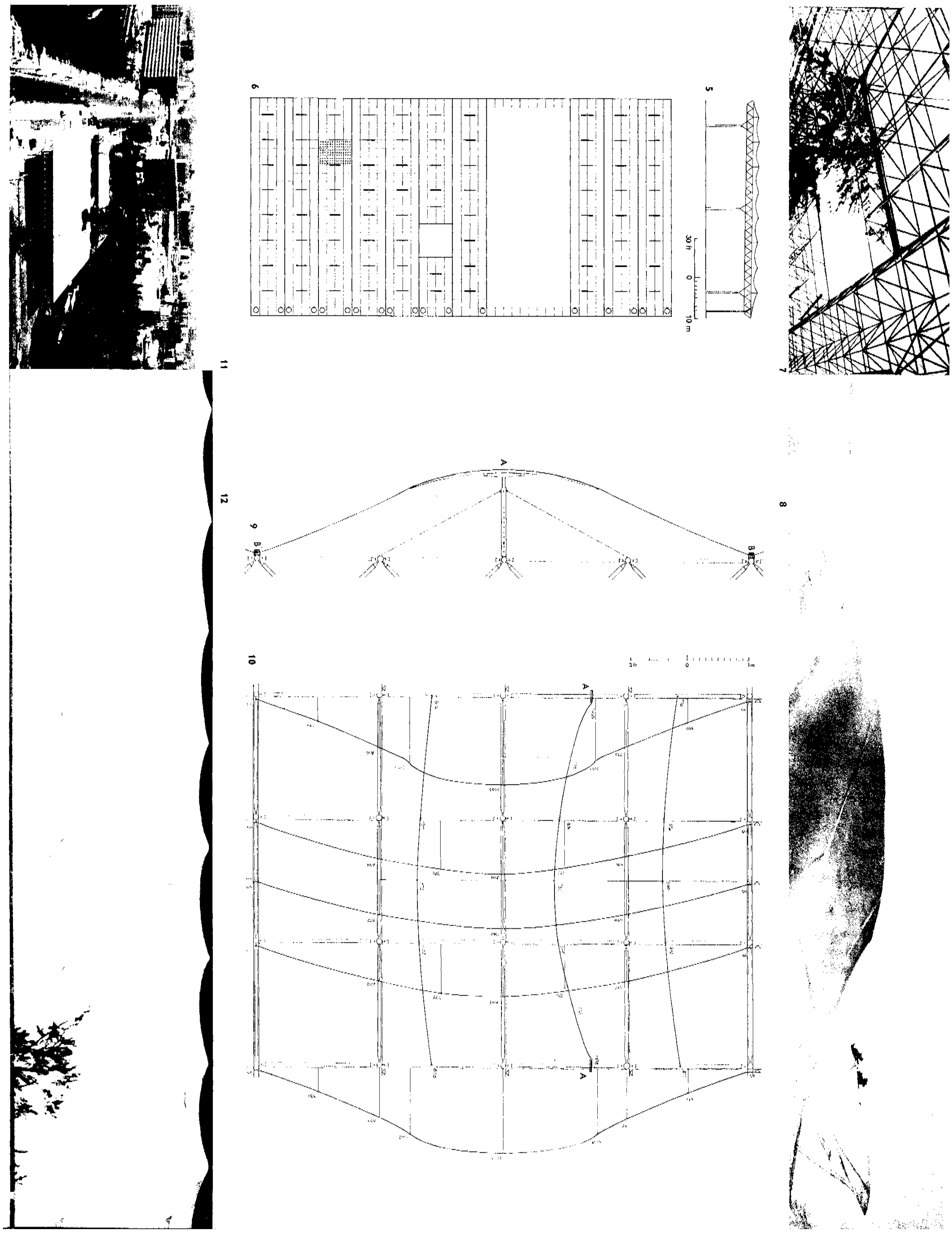


Figure 15: "City Of Tomorrow" Roof Details

4.2. Café Bellevue, Berlin, 1957

Architects:

Frei Otto, Ewald Bubner, Siegfried Lohs, Dieter R. Frank 1957

Dimensions and covered area:

24 m x 36 m, approx. 680 m^2

Purpose:

Cover for the café near Tiergarten next to Bellevue Castle.

Fabric:

PVC coated nylon fabric & cotton duck.

Features:

Flat locally reinforced membrane with edge cables and 18 anchoring cables. Three storm cables running over the surface from one broadside to another. Eight telescopic masts are equipped with poles with leaf spring heads as a ram to hump up the membrane. The ram was made of a stellate arrangement of stacked plywood blades comparable to the leaf springs of an automobile suspension. See also chaprters 4.4 +5.4

Mounting sequence:

> *"The roof membrane, initially plane, was given its characteristic spatially curved shape by pushing it up ("humping") during erection of the structure (6, 7). The flat fabric was spread bay by bay on protecting tarpaulins. Then two telescopic poles were erected in the semi-extended position, the roof membrane was drawn over them, and the guys of the edge cables were secured externally to the foundations (6). Next, the telescopic poles were uniformly extended in a number of operations (7), and in the final stage of erection they were thrust upwards with considerable force by means of hydraulic jacks, so that at the top of each pole a "prestressing" force of 850 kg was transmitted to the roof membranes. Erection took five hours to accomplish, excluding subsidiary operations."(Roland, 1979: 68)*

Observations:

The Café roof was the first humped tent of the kind. It was a pure Otto idea. Apparently he took advantage of the opportunity to venture another basic experiment. In addition to that the arrangement of the main tent surrounded by five hypars was very improvised. The four point sails, had come out of the Stromeyer stock. These are relicts from a former and failed candidature for the Munich Oktoberfest. Basically, the main tent was to cover the infrastructure of the café and allowed for accommodating a limited number of guests. The majority of guests had to take a seat under the above-mentioned sails. As stated before, this tent was newly invented and purely experimental. Not only for being the first true humped tent in the narrower sense of the word, but also for the materials used. The fabric was made from a novel and yet unproven nylon fibres. The original membrane failed after a short time and had to be replaced by a cotton membrane. The spare membrane was taken as an object to closely observe and record the behaviour of fabrics under given conditions. See comments on materials in chapter 5.4.

> Hoechst AG donated the fabric for the first membrane. A PVC-coated perlon weave with a high tensile strength and super white appearance. Not knowing about the noxious side effects the mill had dyed the material with titanium dioxide before spinning. After a few weeks only the membrane failed. The fabric was torn apart alongside a 24-meter crack. Fortunately none of the masts had fallen over and no one got injured. However the membrane had to be replaced. Only two weeks later Stromeyer supplied a spare-membrane out of time-tested cotton. (IL16,Tents, 1976)

Figure 16: Membrane reinforcements, Overview Café Bellevue

The photos I could study seemingly show the difference between the membranes. It looks as though the synthetic membrane had no reinforcements in the areas of the humps, while the cotton membrane clearly shows such reinforcements displaying the bloom pattern of the mastheads.

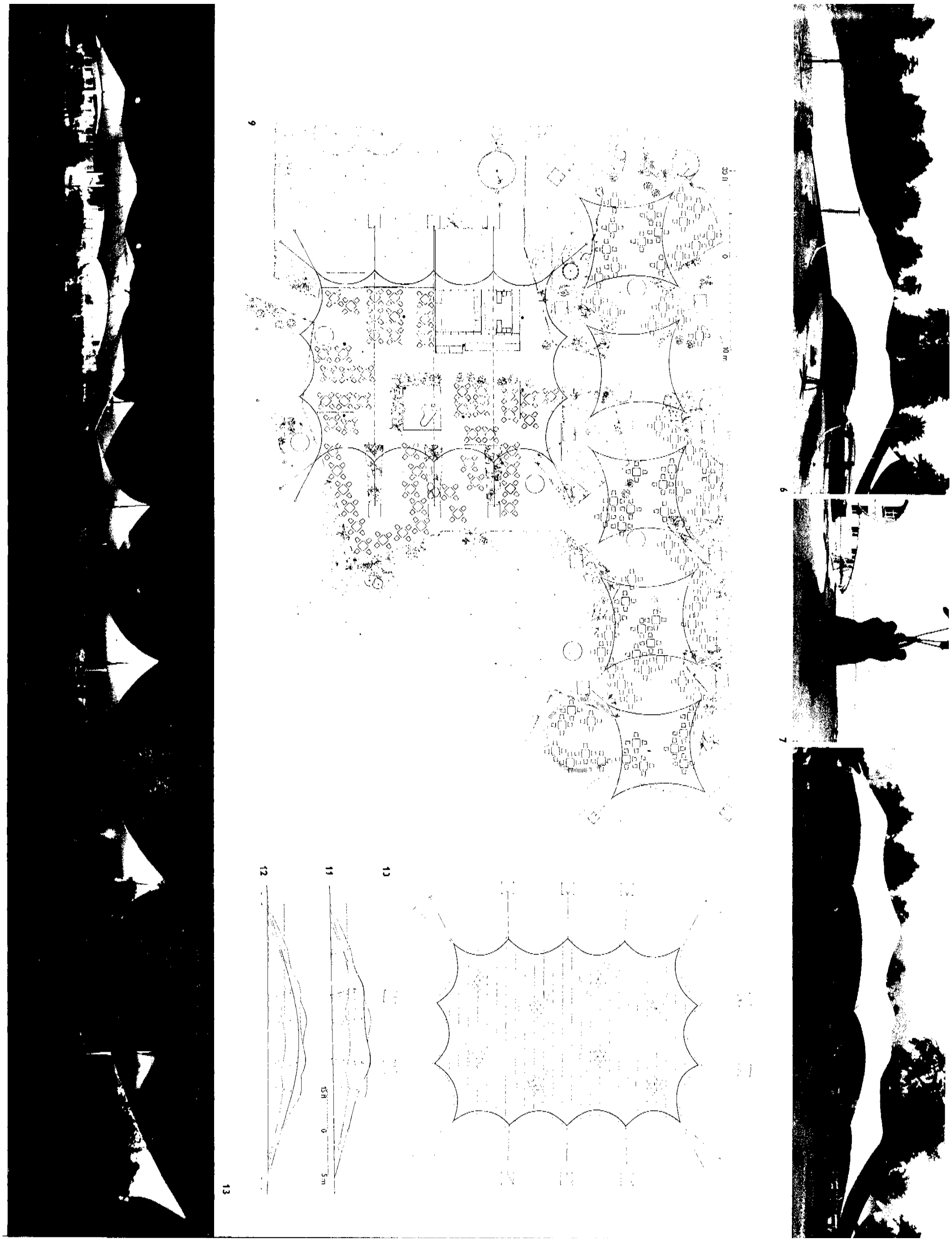


Figure 17: Café Bellevue, Drawing ground view, elevation, Overview by night, Mounting sequence

Another effect of this tent was the impact on the public. Obviously the humped pavilion was so pleasing that it experienced a revival after the INTERBAU. A Swiss architect badly wanted the tent and finally it was sold and transferred to Zurich, Switzerland in 1958. The pavilion was installed on an artificial island, which had been banked up in the Lake Zurich for the purpose to create a special space for the exhibition SAFFA 58[2]

4.3. Orchestra Canopy INTERBAU Berlin 1957

Architect:

Frei Otto, Ewald Bubner, Karl-Heinz Bubner 1957

Purpose:

Shelter to cover the orchestra playing at the INTERBAU inauguration ceremony.

The tent was not planned to persist and was therefore dismantled immediately after the ceremony.

Dimensions and Covered area:

14 x 18 m, approx. 252 m^2

Fabric:

Cotton with synthetic finish

Features:

A freestanding level tent roof, supported by 14 peripheral struts with guying cables. One central mast creates a rounded highpoint. Four funnels, sewed into the membrane, are arranged around the centre. The funnels have a hose and a cable attached to the bottom creating the low points when pulled down and thereby working as a gutter.

[2] SAFFA 58, Schweizerische Ausstellung für Frauenarbeit, 7.17.-9.15.1958

"A membrane out of lightweight plastic laminated tent material was originally spanned in a plane und then, in the middle pressed upwards, and at four other points pulled downwards, creating water drains, - so that a spatial membrane construction was formed with its edge in a horizontal plane, a high point and four low points." (Otto & Koch, Mitteilung Nr. 7 der Entwicklungsstätte für den Leichtbau, 1961: 27)

<u>Observations:</u>

This tent was a last minute order. Hardly three weeks before the INTERBAU started, F.O. received the assignment to build the orchestra canopy for the inauguration ceremony. Beyond that it was supposed to be used for the opening day only, so the building had to be as economic as possible.

"Owing to lack of time to make other arrangements, this structure was erected by Frei Otto and his associates themselves, using the simplest possible resources." (Roland, 1972: 73)

Unfortunately, there are not many pictures available of the tent in action. Most documents are found in the publication EL 7 entitled "Membranes with high and low points" from 1961.

The importance of this structure however requested a proper investigation, which led to the publication that deals exclusively with the design features of the tent and the results of the retrospective research conducted at the EL during 1959-1960. The Orchestra Canopy constitutes a new type of membrane structure named "surface with high and low points" with reference to the above-mentioned publication. See chapter 5.1 EL 7

As to the architecture of the orchestra canopy F.O. showed a remarkable sensitivity. In his comments about the situation around the inauguration ceremony he complained about a steel structure that had been erected right in front of the palace a few days before the ceremony. In his opinion it was compromising the sound interplay between the tent and the palace. See fig. 18. The orchestra canopy was developed exclusively on the basis of a design model. The principles of construction however had been developed earlier along with Stromeyer, Konstanz. In this regard the canopy was a true prototype. Neither preliminary tests nor cutting patterns were made. The beautiful model indeed shows the simplicity and efficiency of the envisioned shape better than any of the existing photos.

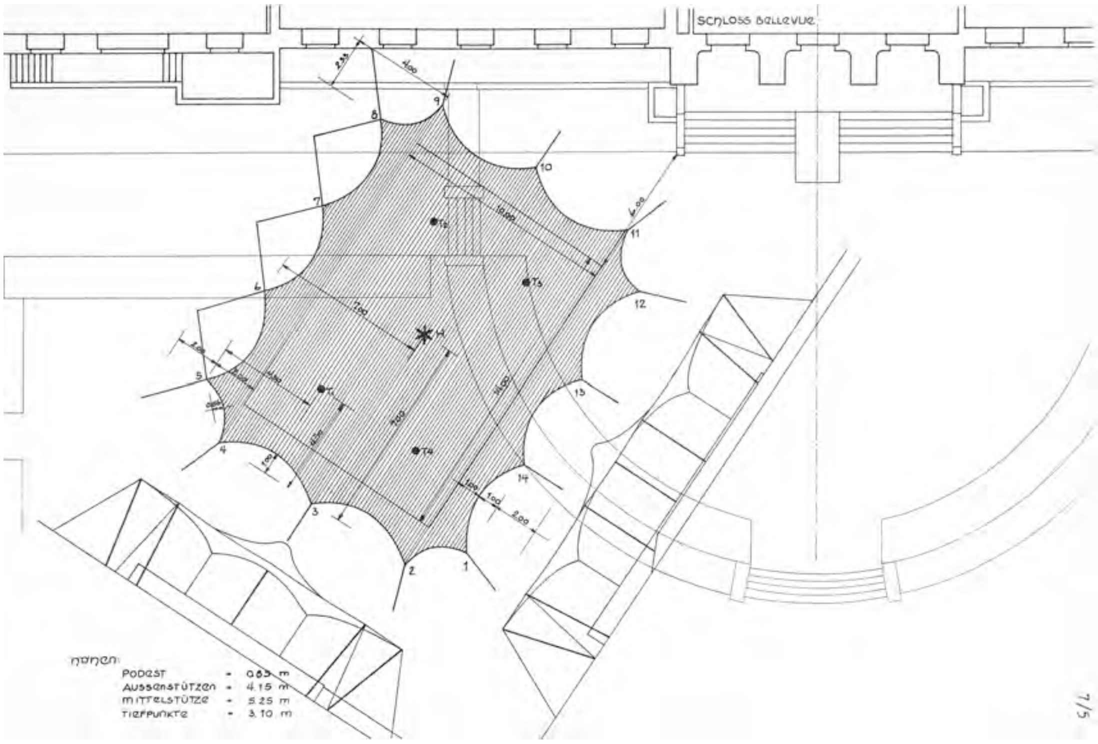


Figure 18: Orchestra canopy, ground view

Figure 19: Inauguration ceremony INTERBAU 57

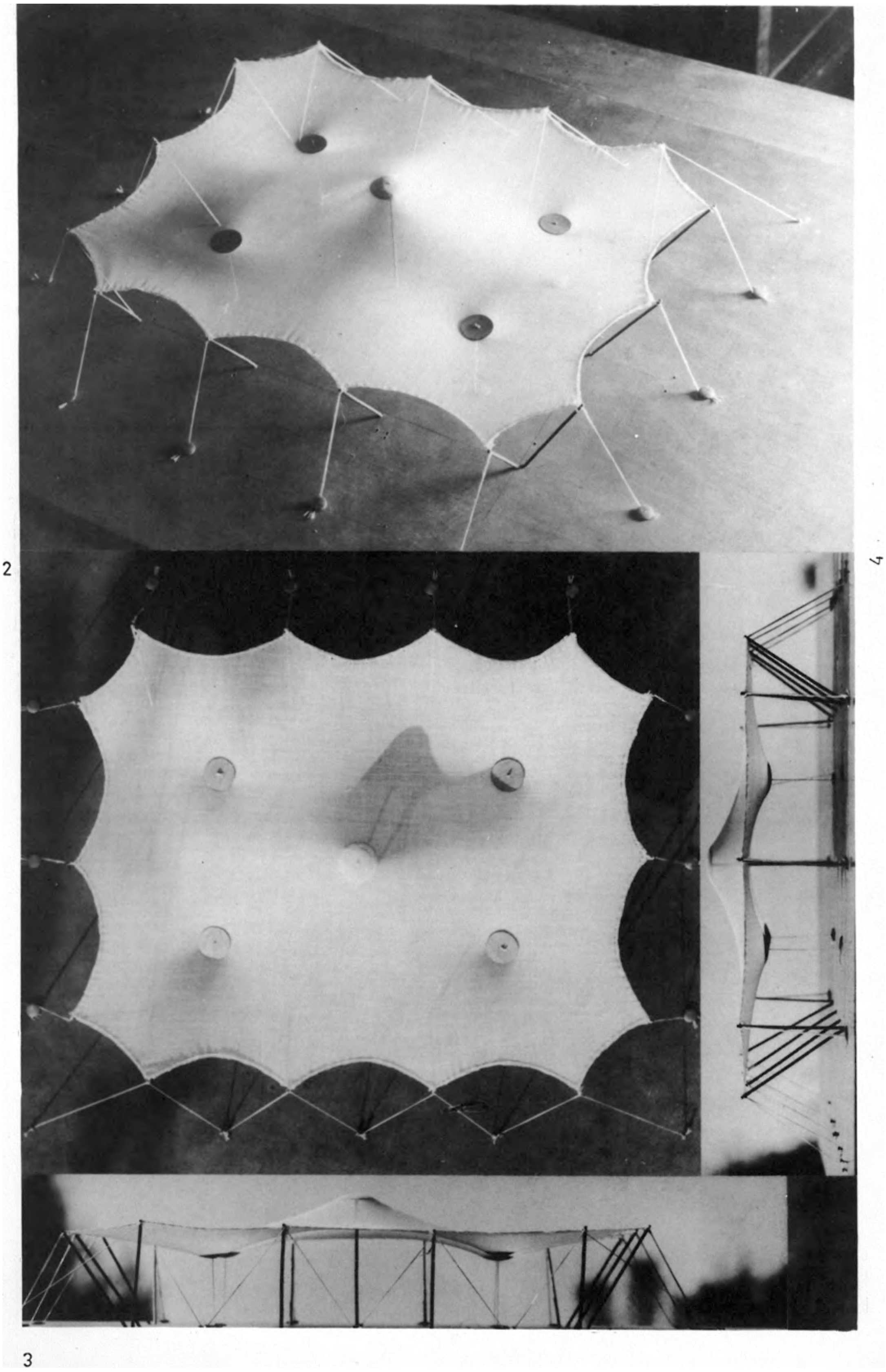


Figure 20: Orchestra canopy design model

4.4. Membrane Hall Hamburg 1963

Architect:

Frei Otto, Hans Habermann, Christian Hertling, John Koch 1963

Purpose:

Exhibition hall for the IGA 63, international horticultural exhibition 1963 Hamburg

Dimensions and Covered area:

64 m x 29 m, 1800 m^2

Fabric:

Cotton 500g/m^2

Features:

The membrane hall embodied a tent roof only, which means that no additional sidewalls were installed. The main supporting and anchoring system consisted of 26 peripheral struts with guying cables, each of them ending on a concrete foundation. For the highpoints eight poles with leaf spring heads are evenly distributed under the membrane to build the humps. Three openings were aligned alongside the middle axis. They were designed as funnels with a parachute-like guying cable arrangement to create the low points when pulled down. The low points worked as a drainage area. A concrete basin was located below every funnel in order to collect the rainwater.

Observations:

The membrane hall for the IGA 63 Hamburg followed the same construction method as it was used for the Orchestra Canopy Berlin. It is a very illustrative example for a membrane with high points and low points. The same pattern was successfully used for a number of later tents. Stromeyer sold a couple of so-called membrane halls, which represented an affordable solution for a large surface low-tech cover. In fact, the Hamburg membrane hall stands for exceptional efficiency.

The overall consumption of material and resources compared to the covered area is impressively low.

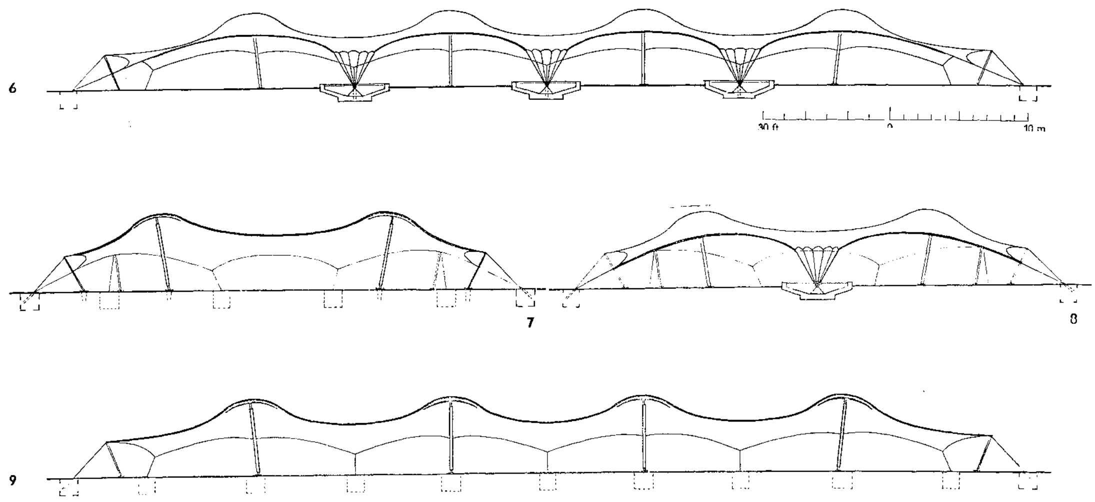


Figure 21: IGA 63 membrane hall, elevations

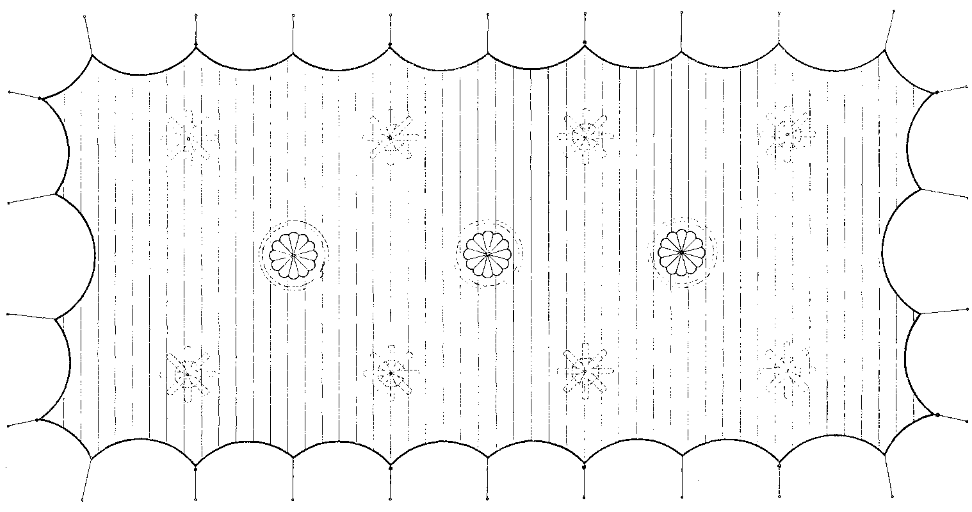


Figure 22: IGA 63 membrane hall, ground view

“Judged in terms of total material and effort, the "membrane hall" at Hamburg is the most efficient roof structure that Frei Otto has hitherto designed. However, the material and time required for making the tension anchorages has not been taken into account …“(Roland 1970: 77)

Some figures[3] are reported:

Covered area:	1800 square meters
Fabric:	2550 running meters (width 1 m)
Weight of membrane:	2100 kilograms (including cables and ropes)
Weight of struts and poles:	2150 kilograms
Global weight per covered m^2:	2.5 kilograms
Manufacturing time:	920 hrs.
Erection time:	253 mhrs.
Erection duration:	15 hrs.

In fact the performance of this kind of concept inspired everyone in the business.

Even though it has never been materialised, Conrad Roland envisioned a great future for membrane halls. In his book "Frei Otto Structures" he concludes the report on the Hamburg project painting a picture full of optimism.

> *"The same structural system could similarly be achieved by "humping" an originally plane prefabricated cable network of constant mesh size, with infilling panels for the roof and glazed walls. This system would be particularly suited for permanent structures of large span. Such cable networks would be made in a factory, the thicker edge cables would be clipped on, and strengthening parallel cables or groups of radial cables could, if necessary, be inserted at the points of support. … In this way it would be possible to develop very economical, easily transportable and yet durable structures of any span, even large spans. The infilling could consist of local materials, so that only the main structural materials would have to be imported. These structures constitute a first step which may offer far-reaching scope for development once the architectural possibilities and economic advantages are generally recognized." (Roland 1972: 76)*

[3] (Roland, 1972)

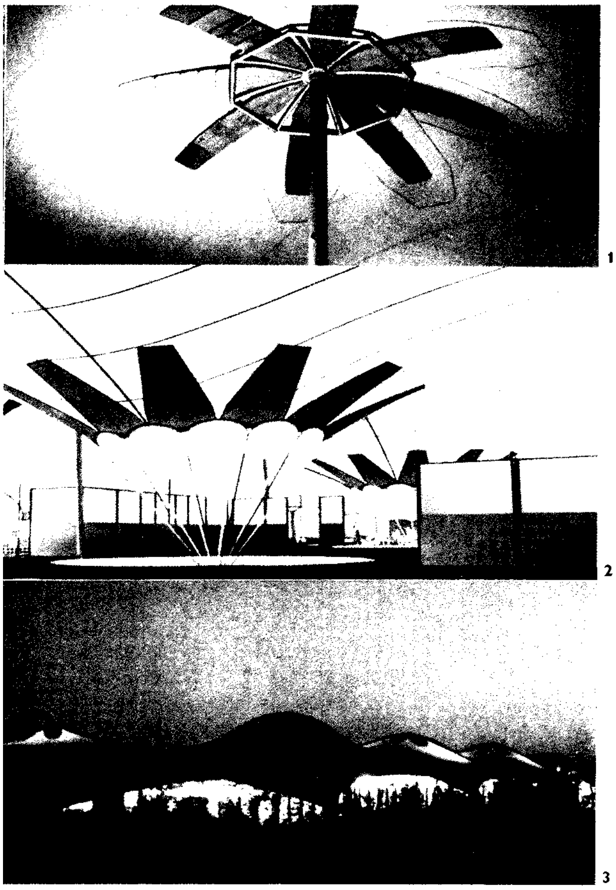


Figure 23: IGA 63 Membrane hall. 1. Leaf spring masthead 2. Drainage funnel low point 3. Overview

4.5. The Humped Pavilion, Cologne 1957

Architect:

Frei Otto, Ewald Bubner, Siegfried Lohs, Dieter R. Frank 1957

Purpose:

The tent is a porch roof giving shelter to the exhibition visitors.

Dimensions, Covered area, confection surface:

App. 12 m x 24 m, approx. 150 m^2, approx. 200 m^2

Fabric:

Cotton

Features:

The pavilion consists of a roof membrane only. Two-piece assembly of a cable reinforced membrane with seven bracing cables attached directly to the ground. Two masts with a globular bearing head create the highpoints. This very elaborate construction can be described as a pole with a spherical arrangement of numerous spreader bars on top. The whole build of the mast and bearing head resembles a lot the seed was of a dandelion.

Observations:

The humped pavilion represents a unique case of a humped tent as such. The extraordinarily pronounced humps are untypical not only in terms of appearance but also in terms of construction. Opposite to the above mentioned cases this shape cannot be achieved by humping up a plane membrane, e.g. by simple deformation of the fabric. A whole sequence of preliminary steps needs to be performed, including form finding, cutting patterning and detailing, in order to succeed with manufacturing and accordingly erection.

However this kind of humped tent remained an isolated case. Given the necessary planning effort it was simply an unaffordable solution for the tent making industry.

Personal comment:

> *In fact this tent must literally be seen as the exception of the rule. Astonishingly enough F.O. once again anticipated the most exotic case of a field in the same breath. Instead of proceeding step by step the genius often had a full survey over an entire subject from the beginning. (Töngi, 2018)*

Form finding and confection:

The Cologne humped pavilion was originally form found on the basis of a rubber skin model. Rubber skin having isotropic expansion behaviour and is an ideal material for high degrees of deformation. In a second step a plaster model was moulded from the rubber model. On the rigid surface of the plaster model a cutting pattern was mapped. By drawing right on top of the model the fabric strip lines including overlaps and inserts, an accurate cutting pattern was achieved. In this case two identical but mirror-inverted pieces of membrane were sewed together. For the rounded caps or humps a separate spherical pattern was generated.

The following figures show the cutting pattern drawing as well as the detail of the spreader bars on top of the mast and the rubber model.

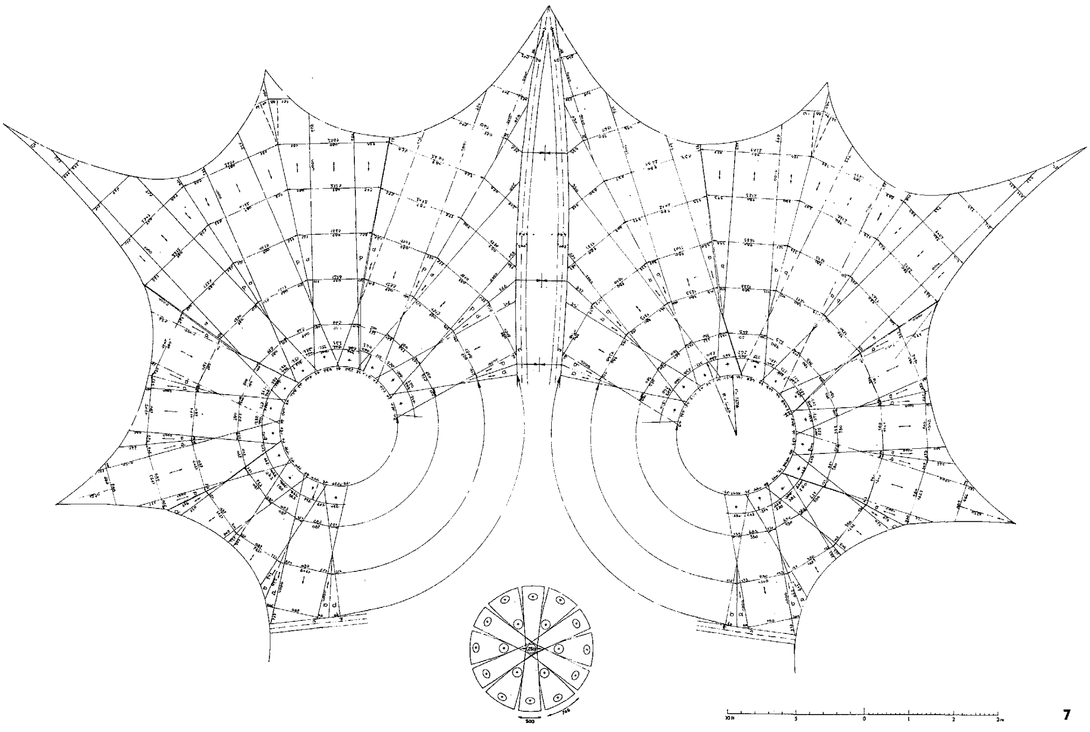
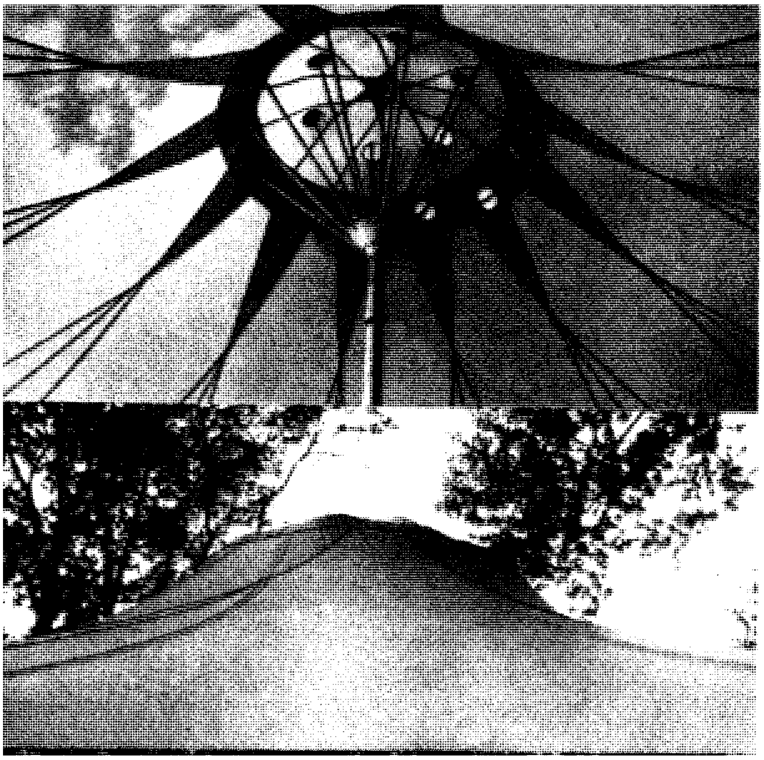


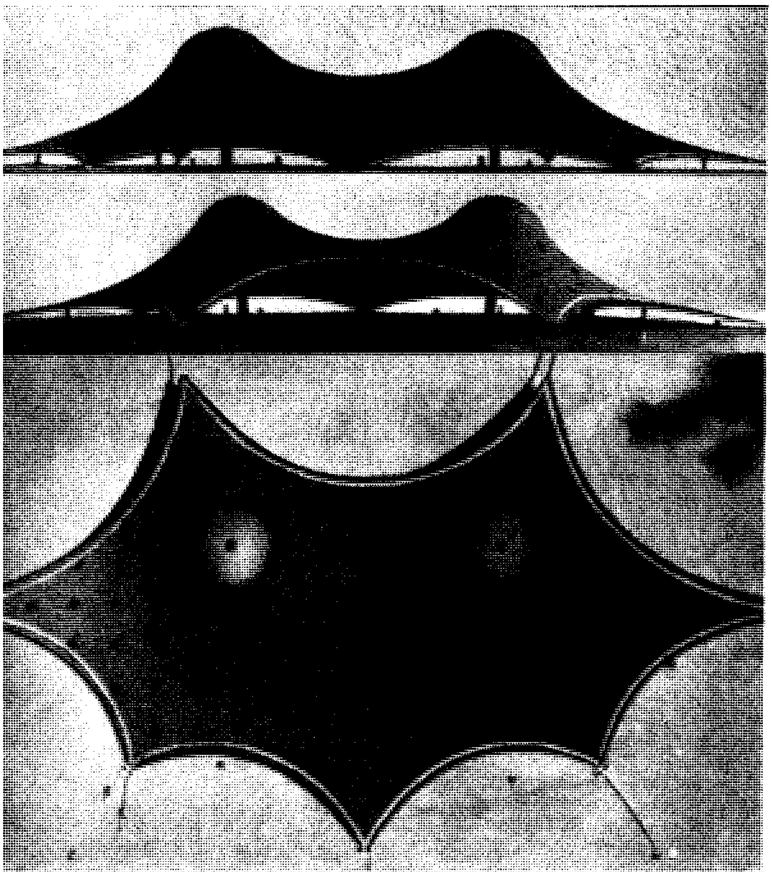
Figure 24: Humped tent Cologne, Cutting pattern



1

2

Figure 25: Mast Details



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5

6

Figure 26: Rubber model

Figure 27: Humped Tent Cologne

5. Fundamentals

5.1. Mitteilung Nr. 7

The M7 or EL7, Mitteilung 7 der Entwicklungsstätte für den Leichtbau by John Koch and Frei Otto was published in 1961 and was entitled "Membranes with high and low points". It is giving a detailed report on the extensive series of later conducted experiments related to the Orchestra Canopy Berlin.

> *"The building behaved at the time of the opening celebration of the "Interbau" generally convincingly. Due to the general implication of construction methods in the years 1958 and 1959, model-analysis was chosen not only to determine the form of the roof, but also it's economy and strength under loading." (Otto & Koch, Mitteilung Nr. 7 der Entwicklungsstätte für den Leichtbau, 1961: 27)*

The two associates Dieter R. Frank und Siegfried Lohs immersed them with great effort into the extensive work and spent two years with experiments and documentation. The building had to be reversely engineered on a laboratory scale since it no longer existed. The following paragraph is a summary of the experiments and findings reported in the above-mentioned publication.

> The experimental arrangement consisted of a plain rubber skin spanned to 10% prestress of its original length. A grid was previously drawn on the rubber skin in order to observe the subsequent deformation. …Four low points and a central high point were arranged as to convert the skin into a membrane. One first finding with rubber membranes was the observation of gridlines i.e. points, moving only vertically during the membrane deformation. (fig. 28) A precise measuring bracket was built to gauge the spots of equal elevation on the membrane surface and transfer them to a drawing plane above the model. Connecting the spots allowed for mapping the contour lines of the membrane. (fig. 29), (Otto & Koch, 1961)

> *"As each contour approaches the high or low point it approximates more closely a circle... In figure 7/14 the most important continuous contour lines were drawn, and, perpendicular to these were drawn the lines of the greatest inclination. With a rubber membrane in the basic spanned condition, in which each point has moved only vertically in the plane of deformation, all stresses in the direction of the contours are equal. In the direction of the lines of greatest inclination the membrane stresses grow with this increasing inclination, as one might recognize from the density of the contour lines and from the radial stress concentrations around the high and low points." (Otto & Koch, Mitteilung Nr. 7 der Entwicklungsstätte für den Leichtbau, 1961: 33)*

Sections through the principal axis were developed to show the membrane curvature. Hence the most interesting therefrom is the section B-T-H-T-B. It is imaging the typical curve progression of a membrane surface with low points and high points. (fig. 31&32)

An equal experiment was conducted as comparison with a membrane of cotton cloth. While all boundary conditions were kept the same, a different form was found after deformation. The cloth was spanned with warp and weft orientation parallel to the main axis. Besides the expected vertical displacement of orientation points the membrane displayed a pronounced lateral deflection of vertices i.e. grid lines. On top of that sharp ridges appeared in the area of the high points. This finding can be seen as proof for the importance of fabric properties in a form finding process i.e. physical modelling procedure. (fig. 37)

In a next series of experiments the membrane was tested under load. An additional apparatus was built and mounted on the above-mentioned measuring bracket. To additionally track contour lines the device was able to bring a set weight on a previously determined location on the rubber skin model and measure the vertical offset under load. Double exposure was used to show both the staring position and the sinking of the membrane after weight being applied. Again the mapping of the contour lines around the indentation was taken to visualize the area of influence of the applied load. (fig. 34&35) (Otto & Koch, 1961)

Summary: The examinations have shown the stress distribution of an originally flat, unstressed sheet as it was deformed into a membrane - for an elastic material such as rubber as well as for cloth. They have also shown which points and areas are to be carefully watched. In conclusion it can be said that this is one of the simplest possible lightweight constructions. (Otto & Koch, Mitteilung Nr. 7 der Entwicklungsstätte für den Leichtbau, 1961: 35)

John Koch at the Washington University, St. Louis, Missouri, USA, conducted additional studies in 1958. The goal of the project was a stress analysis on a deformed rubber skin membrane.

The membrane again was spanned on a level plane i.e. reference plane with 10% of prestress compared to the unstretched length. While the stress division on a flat membrane is uniform, stress asymmetries occur after deformation. Hereby the stress increases proportionally to the distance of a displaced point in question to the reference plane reaching a maximum in the immediate vicinity of a high point and low point respectively. Expectedly the previously painted gridlines on the rubber skin remained straight whereas the squares between the latter shifted into rhomboids after deformation. Hence the stress situation along the horizontal contour lines must be equal. In ground view however the distance of contour lines decreases in proportion to the inclination, which explains the function between stress and form. α being the angle of inclination of the membrane and H being the prestress in the reference plane, the membrane stress M equals the product $\underline{M = H \times \cos \alpha}$ (Otto & Koch, 1961)

According to Hooke's Law, and assuming that the movement of the membrane through deformation was only vertical, the length of the horizontal increment (L) is a measure of the stress in the membrane before deformation, and the measure of stress along the line after deformation is the length of the inclined line (L1) intercepted in the same horizontal increment. The length of the inclined line proportion to the length of the horizontal line is: (7/31 - 1)

Length, horizontal line (L)
Length, inclined line, (L1) *equals the cosine of the angle D between them.*

From this relationship, knowing the amount of the prestressing along the line before deformation, one can obtain the stress in the line after deformation. This was the basic reason for prestressing the membrane a known amount before applying the deforming forces. The tangent (tan C equals M/L) of the angle gives the slope of the curve at any point, and is an index to the forces in the curve due to the deformation. The slope of the curve at any point is a direct measure of the forces through the point. Hence, the greater the slope of the curve at the point, the greater the stresses along the curve at the point. See figure 7/31 - 1. (Otto & Koch, Mitteilung Nr. 7 der Entwicklungsstätte für den Leichtbau, 1961: 39)

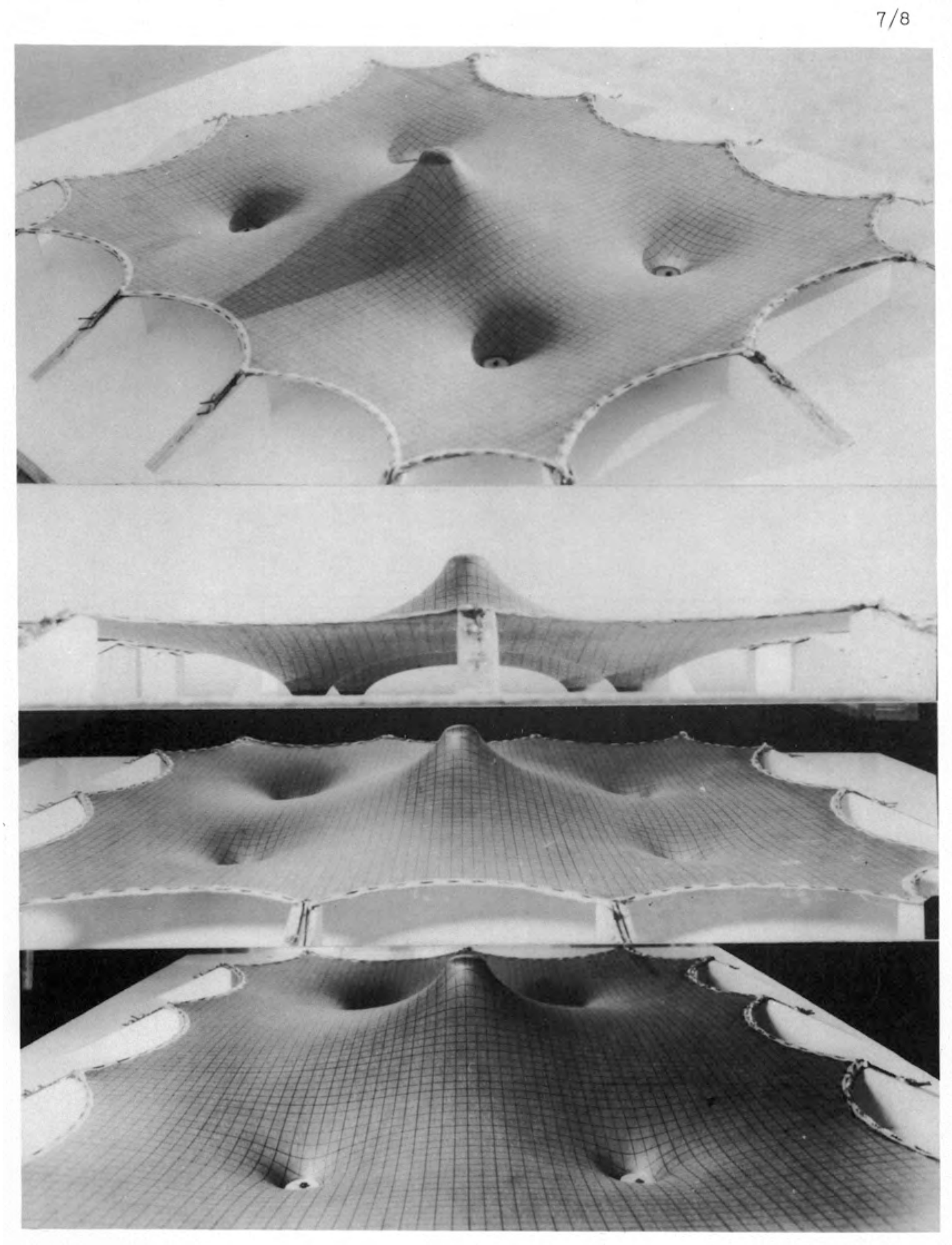

Figure 28: Rubber skin membrane

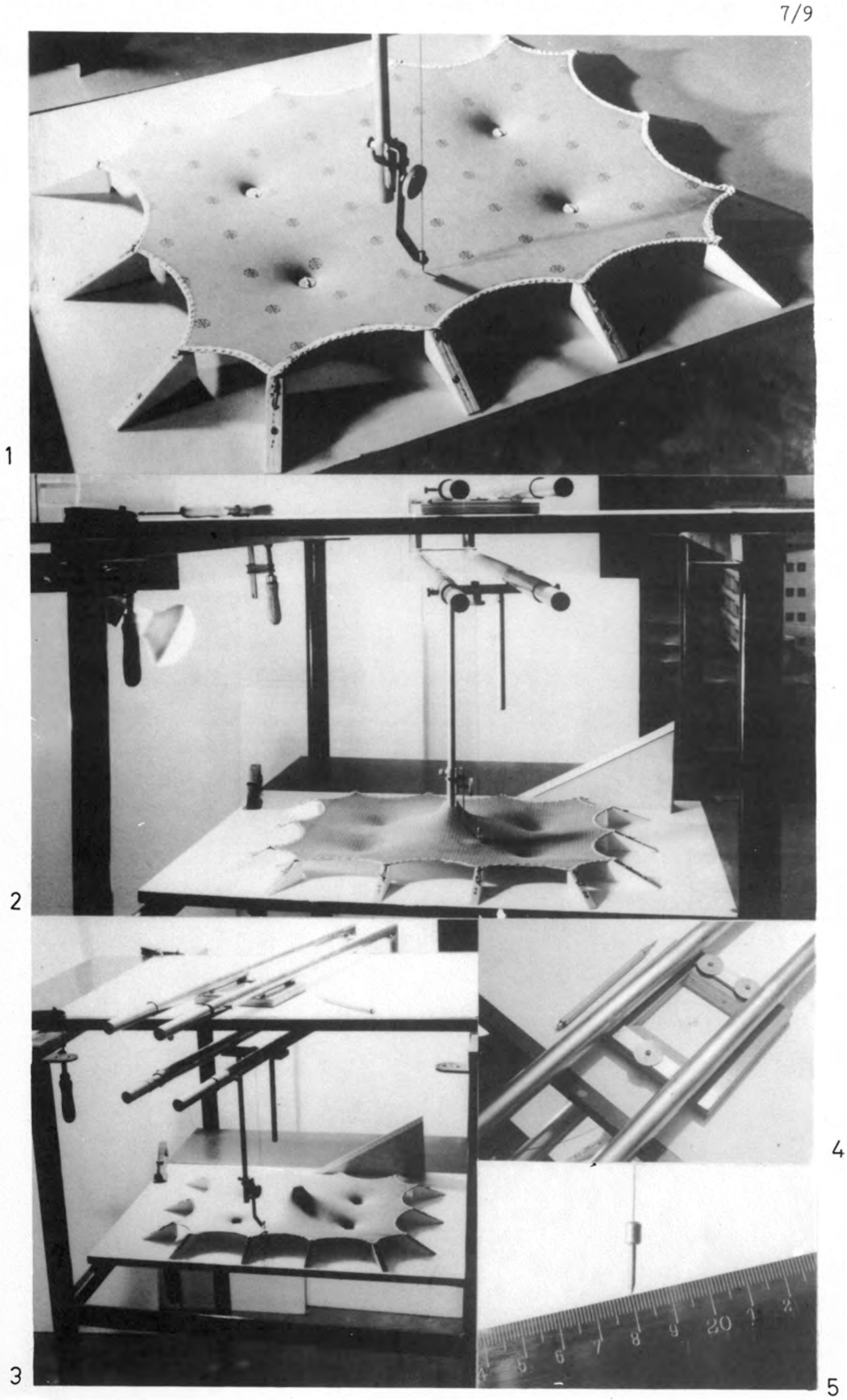

Figure 29: Measuring bracket

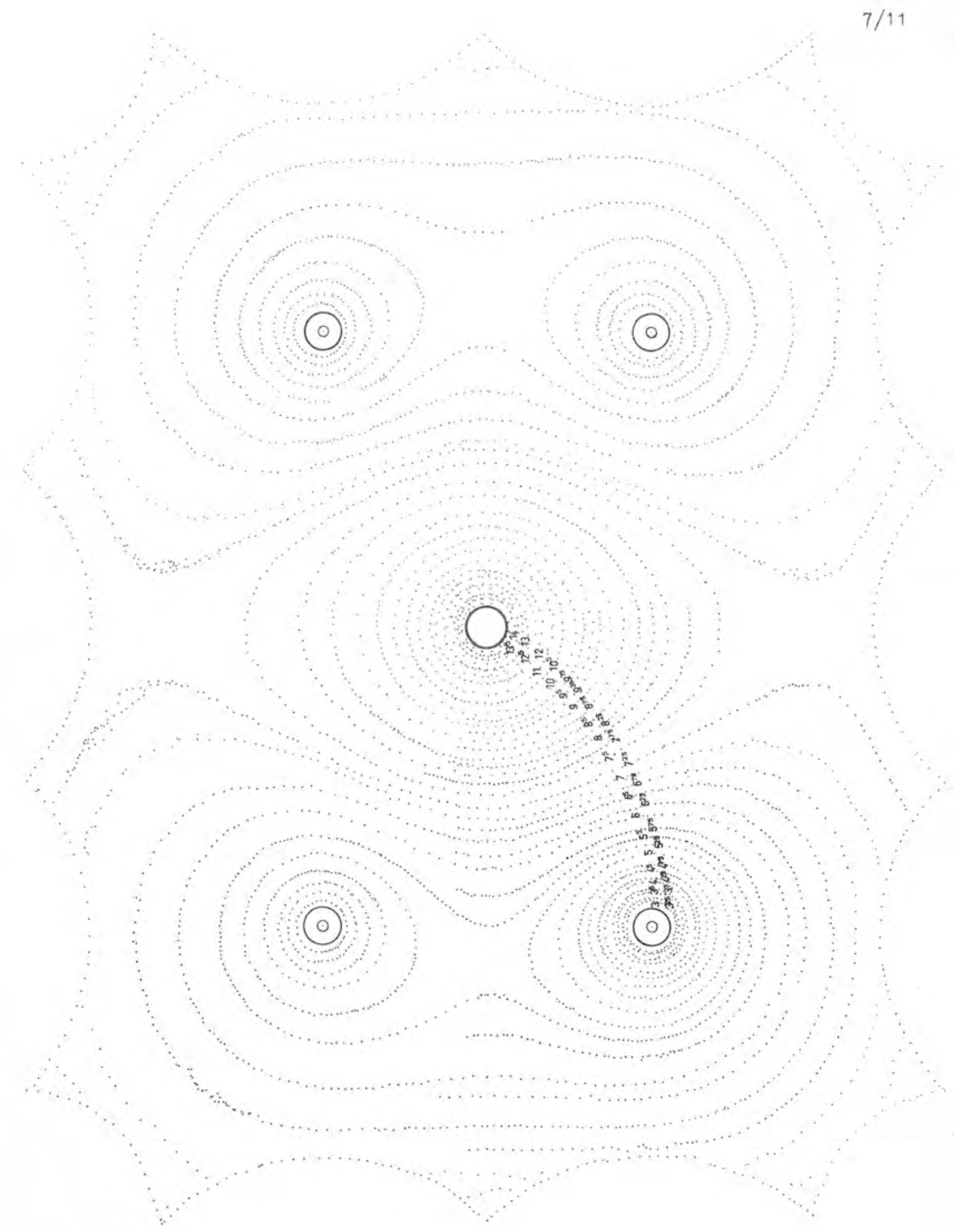

Figure 30: Measuring dots for contour lines

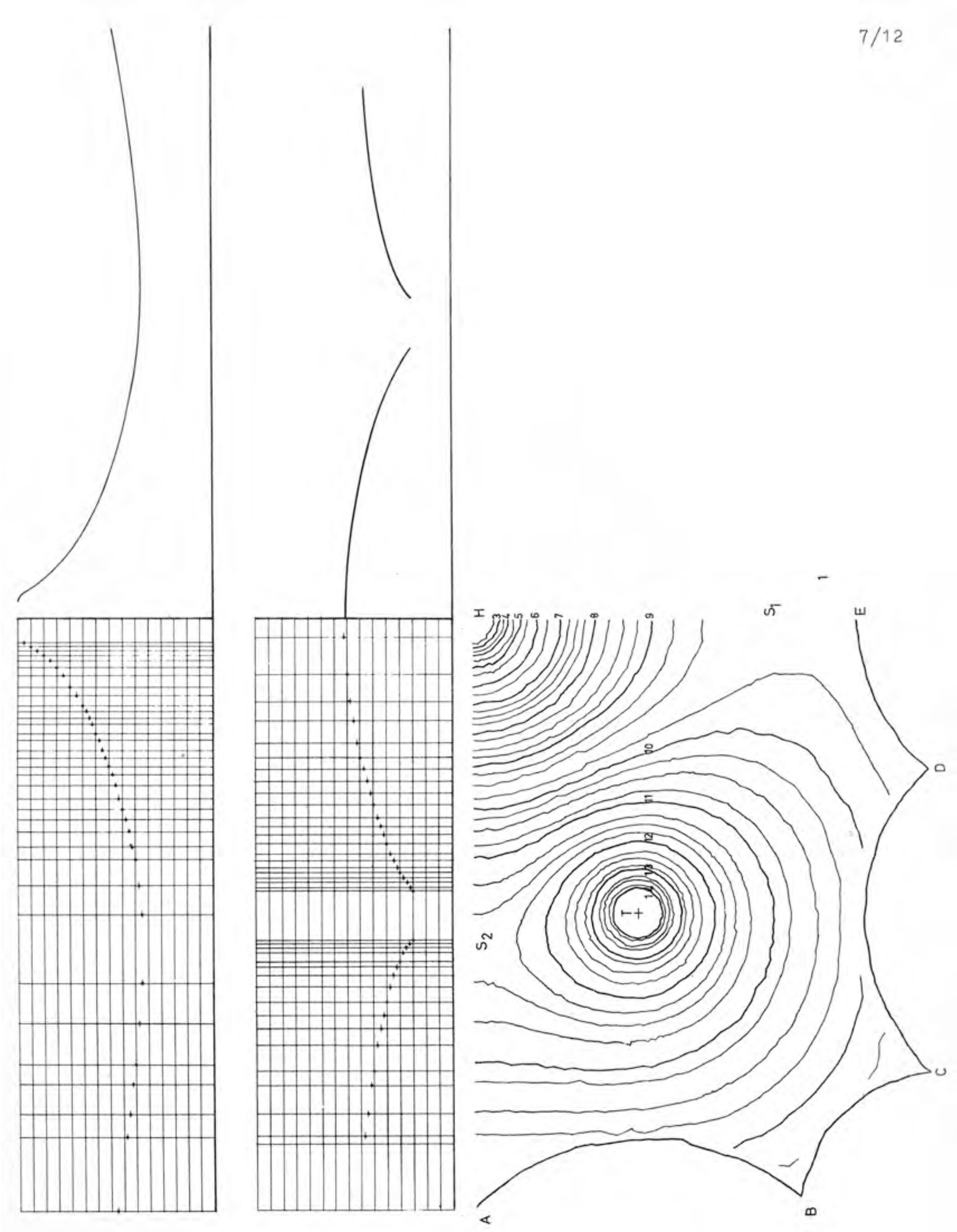

Figure 31: Completed contour lines and sections

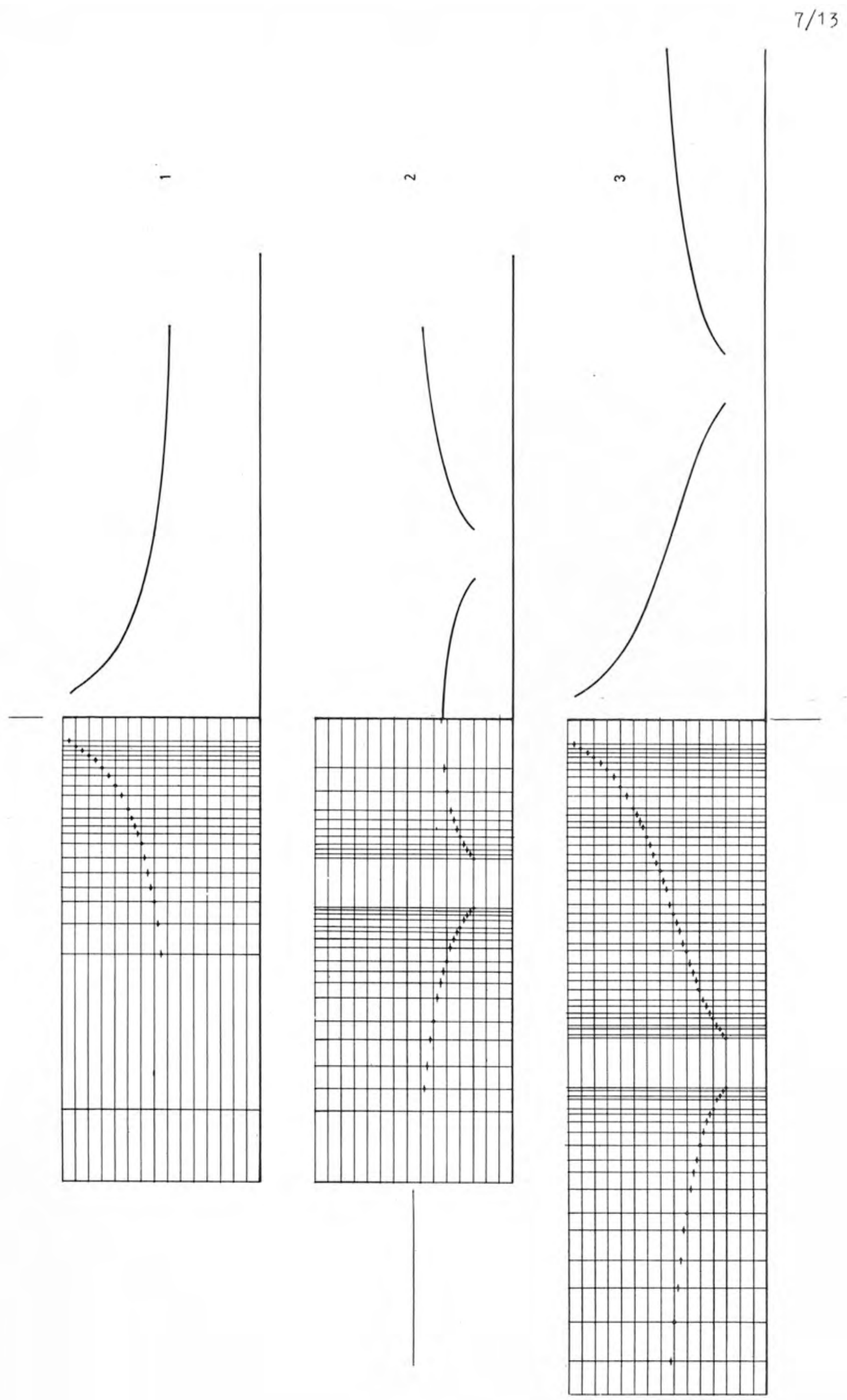

Figure 32: Sections

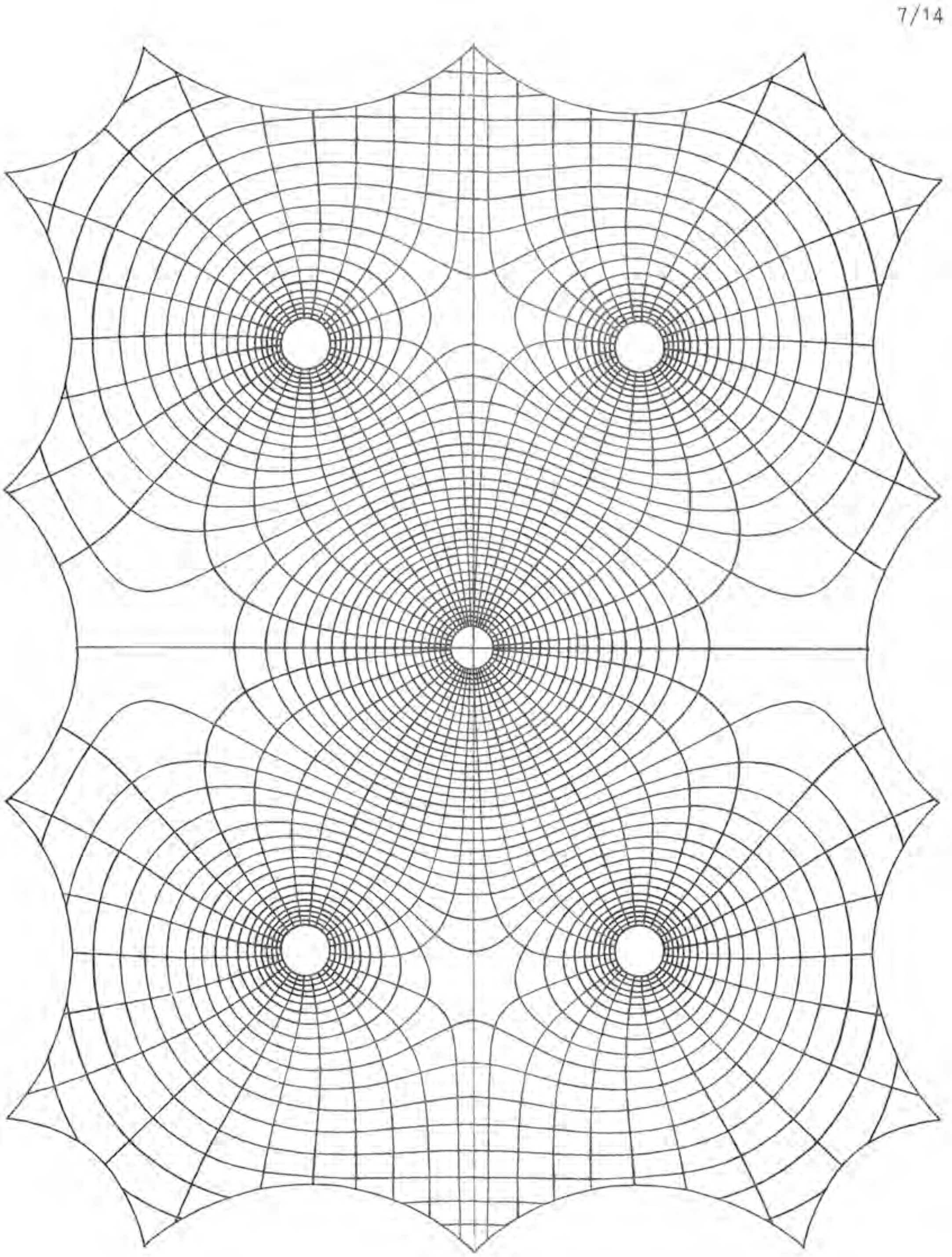

Figure 33: Full image of contour and inclination lines

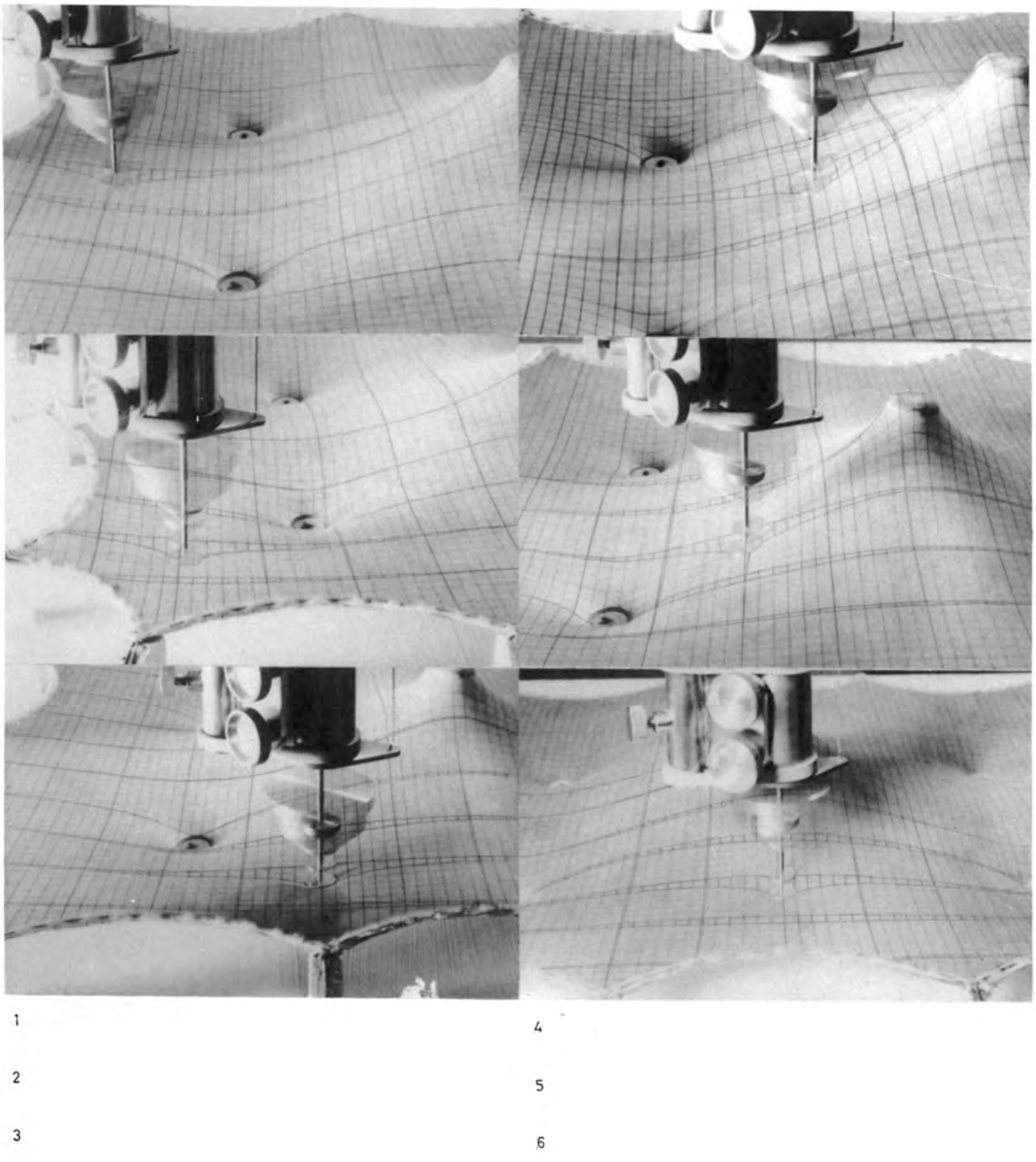

Figure 34: Load application test

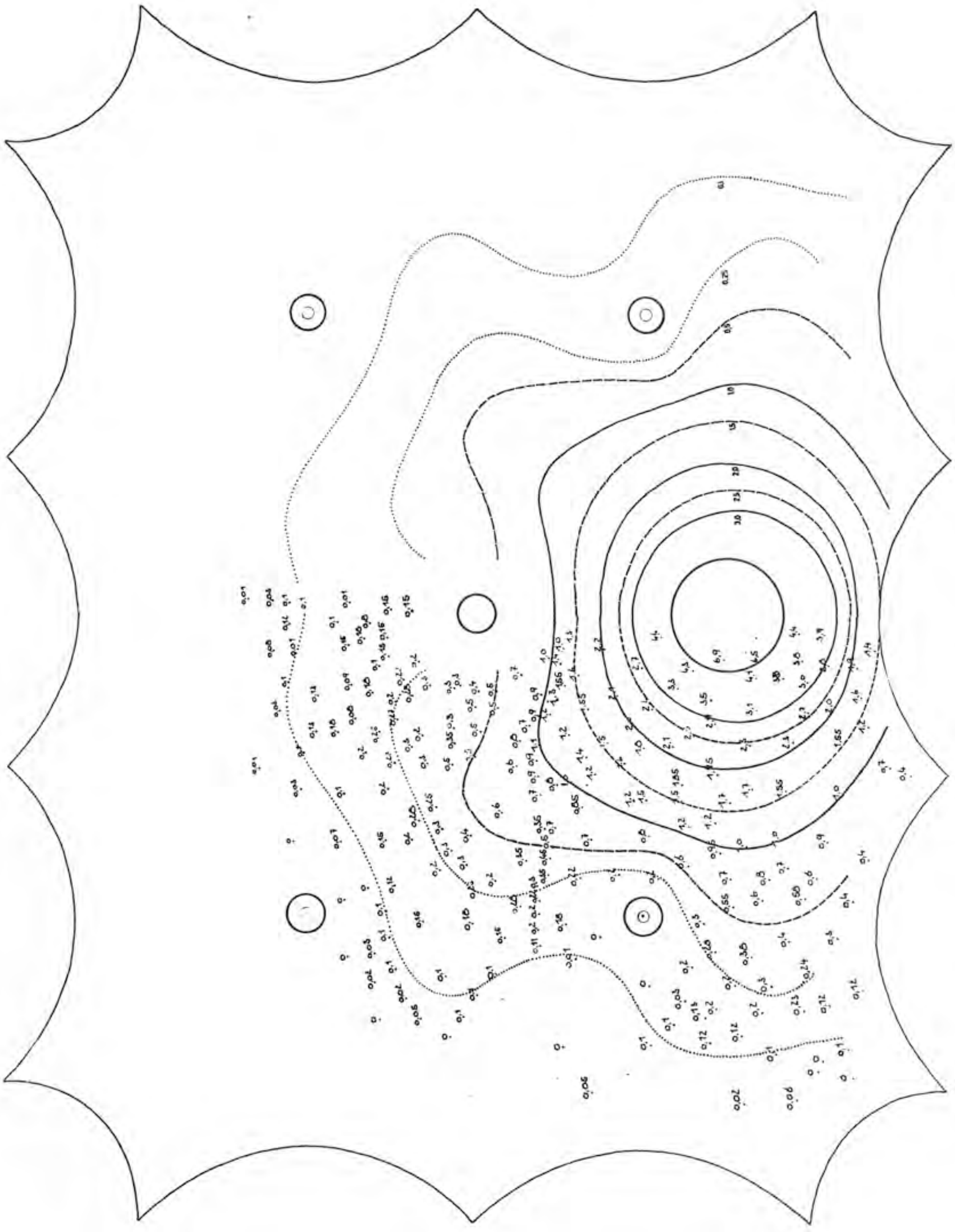

Figure 35: Contour lines of impression

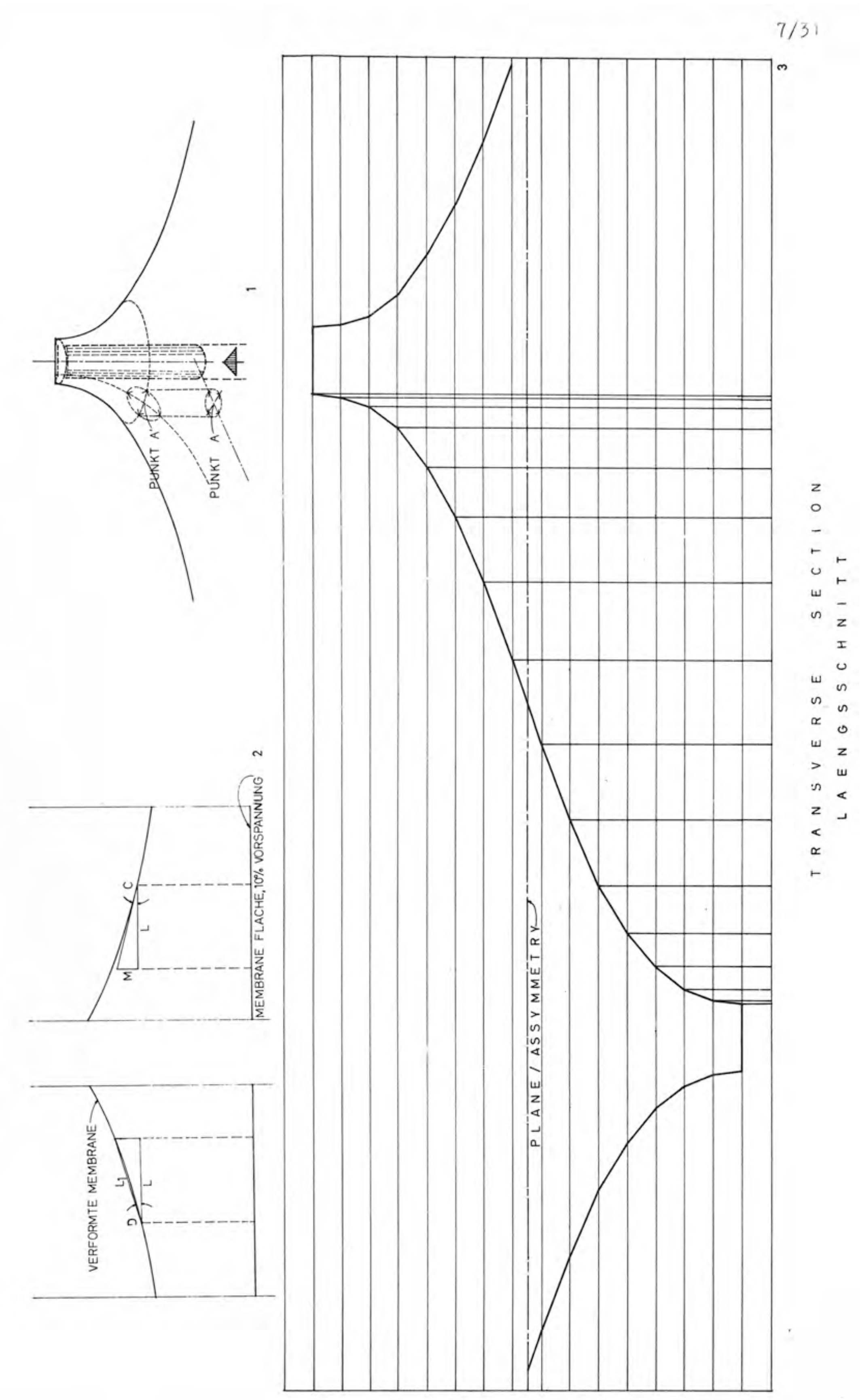

Figure 36: Stress analysis

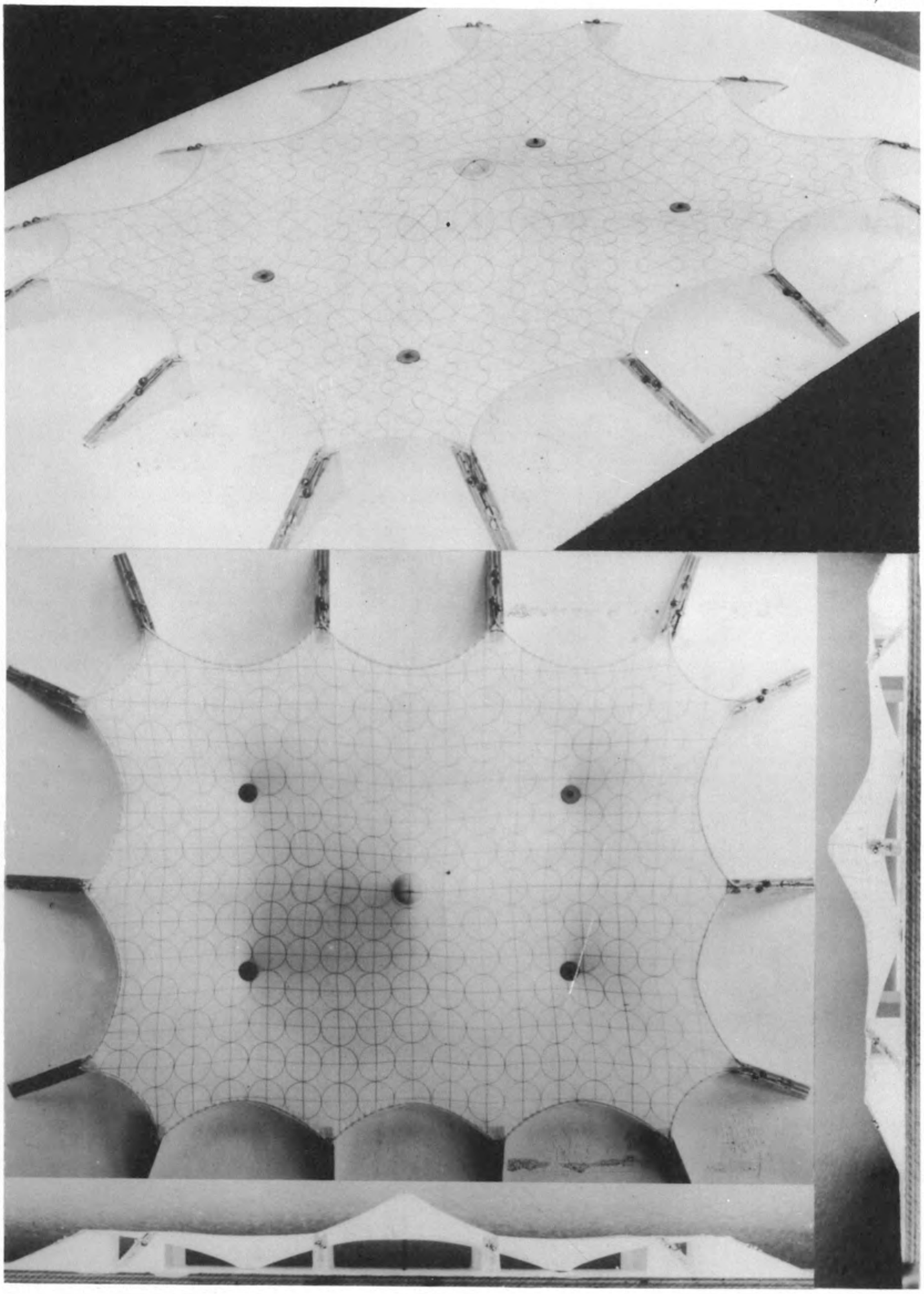

Figure 37: Cotton cloth model

5.2. Definition

The previous chapters on the work of Frei Otto and the presented case studies clearly show the basic categories of humped surfaces. In order to summarize the above mentioned the following key features should be pointed out.

1. A hump is a highpoint in the central or peripheral area of a membrane.

2. A hump is a highpoint created by a direct areal support of a continuous membrane yielding one contact surface between the fabric and the supporting element.

3. A hump is a highpoint of more or less rounded shape having a smooth transition between the supported and the surrounding area of the membrane.

Despite the obvious difference in appearance i.e. shape, a structural distinction is more important to base a classification on. Two basic methods of creating a hump must be distinguished. They mainly differ in the procedure of achieving the desired geometry.

> *"By the exertion of lateral thrust it is possible to apply spatial deformation to originally plane membranes, fabrics and cable networks and thus to produce rigid roof and wall structures. This spatial deformation may be achieved as follows:*
>
> *1. by elastic and especially by permanent elongation of the material, i.e. by once stressing it beyond the elastic range (e.g. in the case of sheet-metal membranes or cable networks with triangular meshes);*
>
> *2. by angular displacement of the net lines of displaceable networks with equal-sized meshes (e.g. in the case of cable networks or rod lattices; see p. 123) ;*
>
> *3. by permanent elongations and angular displacement applied simultaneously (e.g. in fabric).*
>
> *This very simple principle differs significantly from the method of construction applied to the membrane and cable network structures hitherto described whose spatial curvature is produced by special cutting of the component fabric parts. Thus, for example, large upward forces-exerted by means of struts with resilient gently rounded heads-may be applied at predetermined points to tautly stretched plane extensible fabric membranes which are composed of straight fabric strips. In this procedure the membranes are stretched far beyond the elastic range of behaviour of the material so that permanent deformations occur." (Roland, 1972: 65)*

The definition of hump generation proposed by Conrad Roland is including strategies for stiff metal sheets and cable nets along with the typical behaviour of fabric in membranes. For a narrower discrimination of humped membranes (3. ff) it seems to be adequate to introduce two terms of designation. The distinguishing feature is equivalent to the method of highpoint generation.

A. Deformation of a previously flat membrane by means of stress causing strain = Naturally humped surface

B. Sculptured spatial form achieved through elaboration of a discrete cutting pattern. = Artificially humped surface

While the former (A) without effort fulfils the criteria for a humped tent it will be named "natural hump". Whereas the latter (B) will be called "artificial hump" since it requires additional measures for the production resembling standard techniques utilized for membrane structures like cutting pattern and advanced detailing.

For this reasons some authors do not see the case B tents as truly humped tents. I will however stay within the historic terminology and keep listing B type membranes as humped surfaces with particular properties. The following paragraphs illustrate the features and characteristics of both A & B type humped tents.

5.2.1. Natural hump

The local intrusion on the previously flat fabric is performed in the course of erection. The result of humping up with a suitable ram is a permanent deformation.

This deformation is enabled by the capacity of angular displacement between warp and weft strands along with the elasticity of the yarn fibres. As a consequence a membrane after being humped up cannot completely flatten back if dismantled.

This logic has been well documented in the case of the INTERBAU tents and is the classification mark of this category.

The two above-mentioned material properties are the benchmarks to limit the maximal degree of deformation.

"Fabric membranes made from cotton or synthetic fibres can be humped to approximate a maximum angle of inclination of 20° in relation to the initial plane. The attainable height of deformation (hump height) is therefore about one-sixth of the clear span of the membrane. Highly elastic membranes, e.g. rubber membranes, can be deformed more significantly by elastic elongation alone, but are not suitable for roofs, only for walls or ceilings." (Roland, 1972: 65)

The remark by Roland is referring to cotton and vaguely to some synthetic fibres. It sums up the experiences made in the nineteen fifties and the early sixties giving the rough figure of maximum 20° of inclination.

Modern fabrics haven't extensively been observed in the use of humped tents. Most up-to-date materials are based on PES or glass fibres and come with PVC or PTFE coatings. Marketed collections line up numerous grades of stiffness and visual appearance. Obviously any kind of coating is hindering the capacity of angular displacement of the weave along with limiting the overall elasticity of a fabric. At first sight the standard fabrics in tensile architecture are not very suitable for this application. However the latest generation of PES/PVC fabrics but especially PTFE fabrics can be found with suitable specifications. Several collections come as open weave, meaning without or with lightweight coating or with finish only. These fabrics indeed show a considerable capacity of angular displacement and do have enough elasticity. Hence they should be tested and taken into consideration for new projects with humped tents.

5.2.2. Artificial hump

Artificial humps can roughly be characterized as a membrane with a particular highpoint detail. Pronounced humps with steep angles or bigger height generally lead to higher stress concentration in the highpoint area. Hence they usually exceed the allowance of the material to change mesh orientation. As a consequence the geometry can no longer be achieved by deformation only. A classic sequence of design and manufacturing steps is required for realization. These comprise:

- Form finding
- Structural analysis
- Cutting pattern
- Detailing

Most tent builders try to shorten the procedure by simplification. As seen in the example of the Cologne humped tent, a subdivision of the form is made into a conic bottom part and a more or less spherical cap on the top. The subdivision leads to a parting line between the segments. That line divides the membrane into separate cutting patterns for each part. It is even common with many commercial software suites to subdivide the form finding into two independent parts and to re-join for assembly.

Another common simplification is the assumption of a circular two-dimensional parting line between bottom portion and cap portion. Generally all conic membrane shapes apply this logic for the highpoint design. The latter cases of course use a stiff a ring element as boundary to attach the membrane. A covering element, which is neither necessarily rounded nor always made of fabric, is required to close the resulting peak hole.

In case of a fabric-covered highpoint the hump-generating ram i.e. masthead is always a rounded close to spherical object allowing the membrane to run over the hump area. The natural strip order of a cutting pattern indeed is a fan-shaped layout, common with all conic shapes. The resulting seam diagram is a proven measure to lessen stress peaks commonly occurring with steep geometries. If the cutting pattern is subdivided in cone and cap area as two different patterns or if the strips are running uninterruptedly from the bottom to the pole like a longitude is a pattern maker decision. Material properties and geometry steer the possible need of local reinforcements.

The big disadvantage of the above-mentioned simplifications is the limitation to uniform shapes of humps. Reducing the parting line to a circle implies a spherical ram with vertical working direction only and a strictly level i.e. symmetrical boundary around the highpoint. Any freeform ram, be it a somehow elliptical or asymmetrical body i.e. solid body, leads to a three-dimensional curve as parting line between supported portion and the surrounding area of the membrane. An additional complication occurs when a highpoint member is inclined or if the general topography of the design comprises undulations e.g. altering heights of edge points. The realization of such designs is demanding yet feasible by the use of computational methods, however not necessarily within reasonable effort.

As to confection i.e. patterning of artificial humps, the whole line up of today's available fabrics is a possible choice. A possible restriction being made for glass fibre based fabrics. Glass fibre fabrics are known for their extreme brittleness meaning their sensitivity for breakage when folded or tensioned over edges. In the transition zone from supported to surrounding area in a membrane surface sharp edges may occur. The vertical displacement of the membrane under load changes the angles of support to a degree, which potentially damages the structure of the membrane fibres.

5.3. Typology

Humped surfaces have their place inside the typology of membrane structures. Several aspects need to be taken into account to make a proper placement. Using the classification on structure systems of Heino Engel allows for general placement within the systematic of structures:

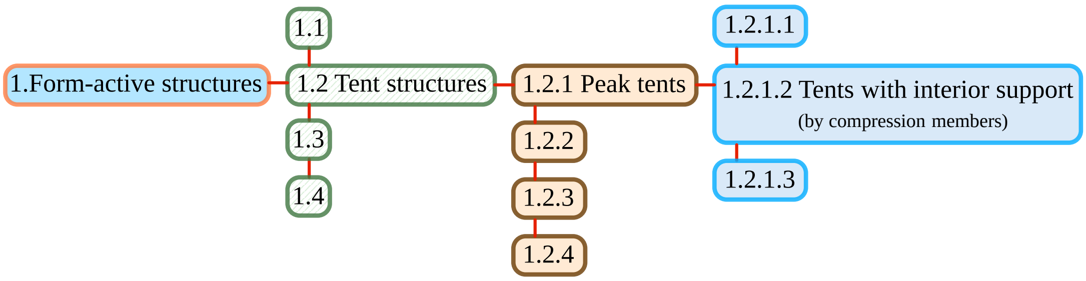

Table 5-1 : Form-active structures 1.2.1.2

Engel does not particularly refer to the details of a high point i.e. peak but he distinguishes between direct and indirect support. The former 1.2.1.2 are all systems with direct interior support meaning; a compression member is working as a strut between ground and membrane.

A second group, the indirect support tents 1.2.3 also exist as humped tents. They can be either exterior constructions 1.2.3.1 or interior constructions 1.2.3.2. (Engel, 1997) The INTERBAU Restaurant (chap. 4.1) is one example for a 1.2.3.1 structure where the supporting elements rest on a joist. (Engel, 1997) The same can be done from the exterior hence the main bearing structure has to be a superstructure with elements locally perforating the membrane. The systematic tree according to Engel looks as follows:

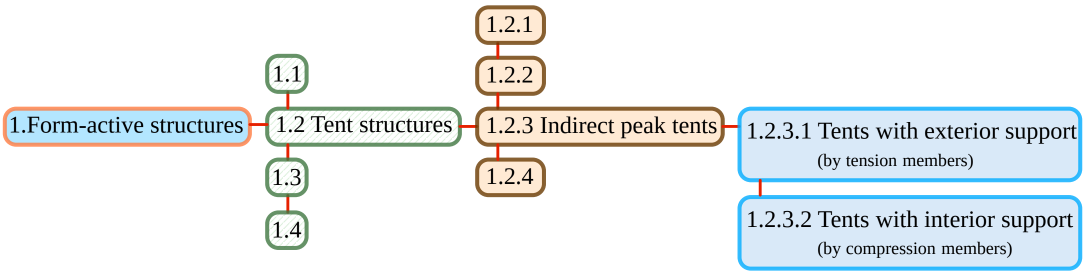

Table 5-2: Form-active structures 1.2.3

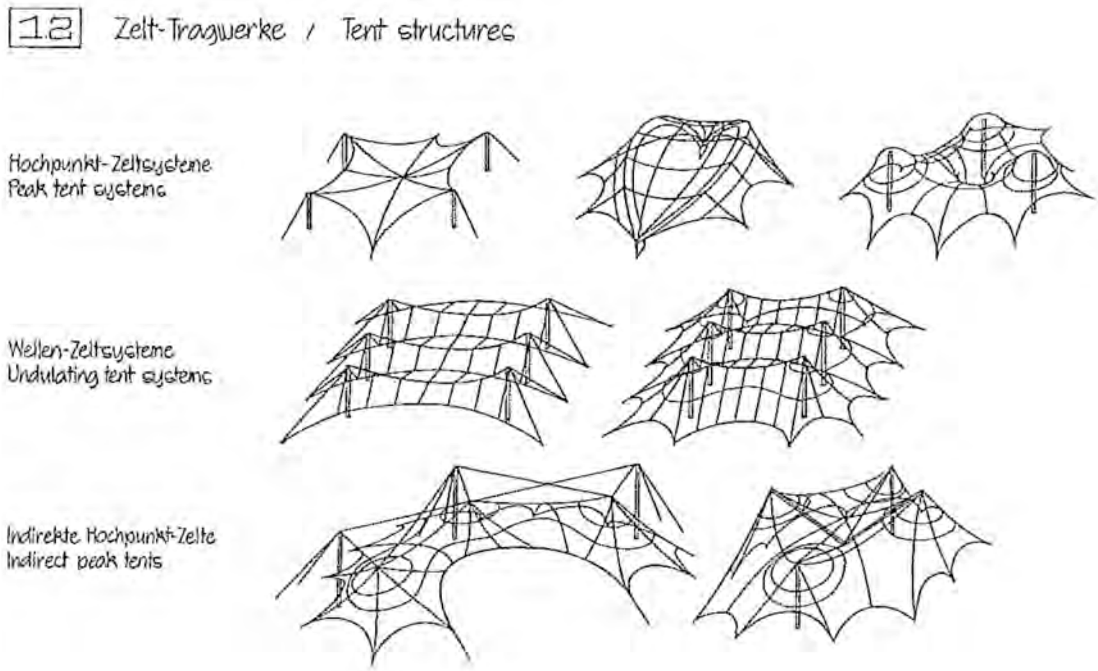

Figure 38: 1.2.1 peak tents - 1.2.3 indirect peak tents

Another aspect of the typology within the narrower systematic order of peak tents according to Engel is the tent topography. Even if not systematically relevant to Engel, a distinction of different peaks makes sense since completely different construction methods for highpoint creation are involved. The topography i.e. the highpoint geometry along with the sequence of highpoints is depending on the geometry and the location of the supporting element. In case of a humped tent shape and stiffness along with the size of the masthead are decisive criteria.

The following table is supposed to give an overview on the design criteria for mastheads.

SHAPE	GENERAL	GOAL	MEASURE
Geometry	Rounded, spherical or arched geometry	Stress distribution	Smooth transition from supported to surrounding area
Edge radius	Maximum possible local edge radius	Membrane Protection	Prevent from incising the membrane avoiding abrupt edges.
Size	Ratio hump size vs. tent surface	Structural equilibrium	Moderation of location distribution and radius

Table 5-3: Shape criteria of mast-heads

STIFFNESS	GENERAL	GOAL	MEASURE
Rigid	Compression Element	Stability under max working load	Cross-section of mast, member stiffness
Flexible	Resilience	Ensure consistent geometry under motion	Material combination and arrangement

Table 5-4: Stiffness criteria of mast-heads

As far as covered by the 1957 tents including the 1963 membrane hall, most of the mast-head builds are explained and illustrated by Ewald Bubner in his 2007 publication *membrane construction connection details*. (Bubner, 1997). All of them fulfil one or a combination of the above-mentioned characteristics of shape and stiffness. However, quite a few are not commented since they figure as variation of one of the basic types. Either they have an inverted application i.e. being a low point or it is a matter of an indirect use according to Engel. (Engel, 1997)

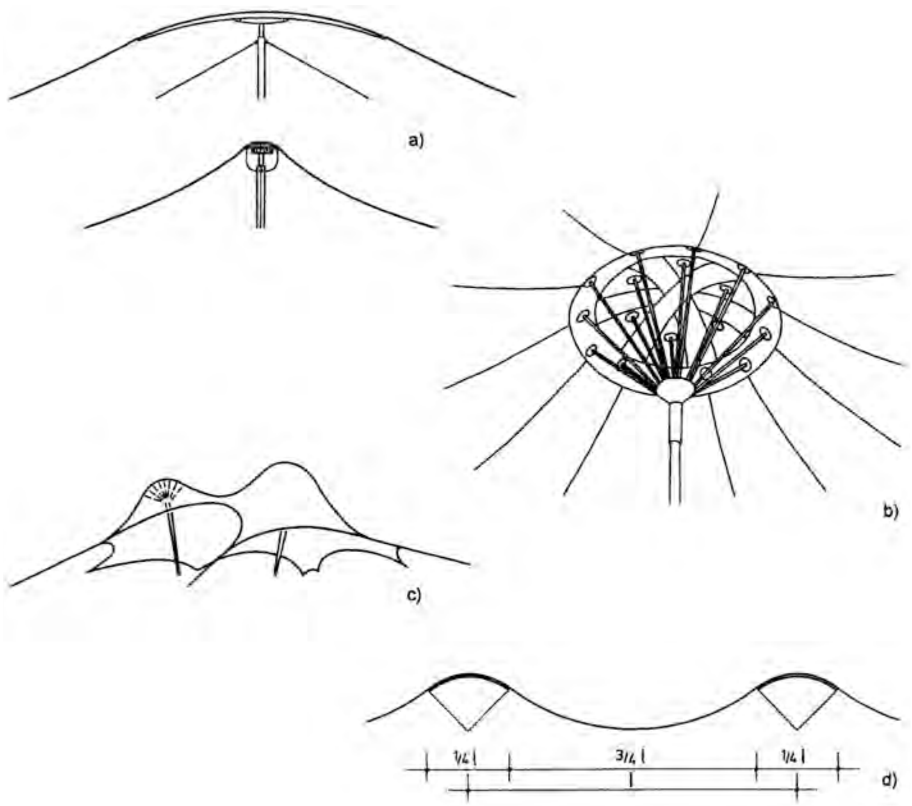

Figure 39: Arched beam „coat hanger“ a), branched spreader bars b) & c), hump distribution d)

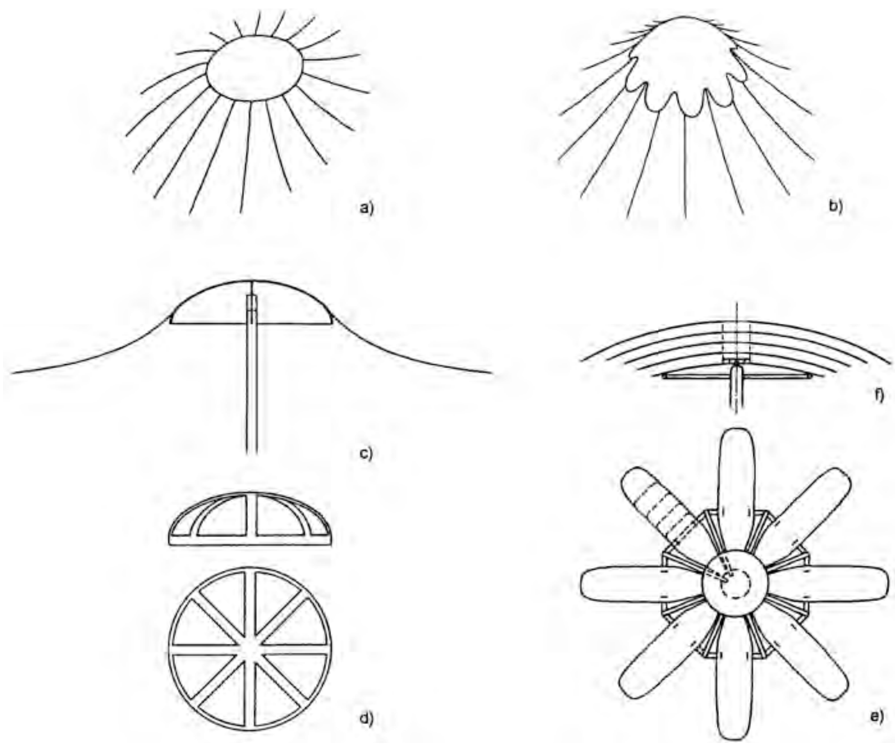

Figure 40: Boiler end calotte c) tin strip umbrella d) leaf spring stack f) leaf spring flower e)

PROJECT	MAST-HEAD	FIGURE	FUNCTION/APPLICATION
City of tomorrow	Coat hanger	Fig. 29 a)	Large span arched support
Café Bellevue	Leaf spring flower	Fig. 30 e) f)	High compression forces, adaptive geometry
Orchestra canopy	Boiler end calotte	Fig. 30 c)	Small and rigid support surface
Membrane hall	Leaf spring flower	Fig. 30 e) f)	High compression forces, adaptive geometry
Humped pavilion	Branched spreader bars	Fig. 29 b) c) d)	Large lightweight and rigid supported area

Table 5-5: Mast-Head builds

5.4. Materials

Stromeyer GmbH, Konstanz, manufactured all the tents of the aforesaid era. The company had their own weaving mill and produced their proprietary fabric.

Unfortunately the Stromeyer Company bankrupted in 1973. The liquidation proceedings extended to a time stretch of more than eight years and ended up in a partition of the company's divisions. In the course of the years a lot of information got lost. Things were possibly not archived and former staff have deceased. It was not possible within the reach of this thesis to acquire thorough information on technical details as to fabric specifications used or fabric finishes utilized with Stromeyer.

Even if not completely handed down, it is likely that Stromeyer worked exclusively with cotton. However the 1950s was the time of upcoming synthetic fibres and a few of them were also tested in F.O. tents. (chap. 4.2)

One inquiry concerning the Stromeyer tent fabrics quarried interesting information on cotton.

Thanks to Mr. Horst Duerr, former technician with Stromeyer and CEO of IF Group, a contact to R. Fuchslocher, former head purchasing agent at Stromeyer was made and basic information on cotton could be obtained.

<u>Standard Stromeyer Cotton Tent Fabric:</u>

- Weight g/m^2: up to 600
- Tensile strength (Mp/m): 3-4
- Failure strain warp/weft: 10/30%
- Finish: Water repellent, fungicide,
Flame retardant, low flammability
DIN 53907, 53382

Coatings are unknown. F.O. misleadingly mentions coatings, yet finish is more likely the appropriate term for the fabric refinement current at that time. (Otto, Burkhardt, & Schmall, IL 16 Zelte Tents, 1976)

In terms of modern tent making i.e. membrane structures, no research was done relating to the selection of fabrics to make humped tents. A few assumptions were made based on the general observations on deformation of weaves. (Chap. 5.2.1)

For the sake of completeness and for comparison purpose however the specifications of a up-to-date PTFE-fabric shall be listed. SEFAR® is a renowned brand for PTFE-fabrics marketing a proven product line-up for tensile architecture applications. As already stated in chapter 5.2.1 the open weave fabrics are seemingly suitable for a natural hump due to ideal capacity of angular displacement of warp and weft. The EL-30-T1-UV along with the EH-35-T2 comes with comparable specifications as the above-mentioned Stromyer cotton fabric.

SEFAR® Architecture EL-30-T1-UV:

- Material: PTFE (Polytetrafluorethylene)
- Finish: 100% Fluor polymer
- Weave: Panama 2:2
- Weight g/m^2: 320
- Tensile strength (N/5cm): 2000/1800 EN ISO 13934-1
- Failure strain warp/weft (%): 13/13 EN ISO 13934-1
- Water column: > 2000

SEFAR® Architecture EH-35-T2:

- Material: PTFE (Polytetrafluorethylene)
- Finish: 100% Fluor polymer
- Weave: Plain weave 1:1
- Weight g/m^2: 550
- Tensile strength (N/5cm): 4100/4000 EN ISO 13934-1
- Failure strain warp/weft (%): 23/19 EN ISO 13934-1
- Water column: > 3000

6. Experiments

Against the background of the preceding chapters humped surfaces appear as very important type of structures and an even more an interesting field for architectural considerations. In order to promote the subject and to achieve a deeper comprehension, it is a necessity to undertake physical experiments.

Whether covered or not covered in the history of humped tents a number of tests are essential to either be reproduced as a well-known method or to be tried out as something new in an experimental approach. Typically, the aforementioned examples (Chap. 4) represent a limited variation of shapes and topographies. Regardless of representing a natural or an artificial hump all cases have three features in common.

1. In terms of a peak tent with direct or indirect support, they all have central highpoints; located somewhere inside the covered surface and not near the periphery.
2. In terms of a tent structure in general, they all have a more or less level arrangement of edge points around the periphery.
3. Besides the similarities of boundary conditions a third aspect is noticeable. All these tents use a near spherical or arched mast head to support the membrane. Basically two major geometries were described all of them representing more or less an abstraction of a sphere or a cut out of a torus. (Chap. 5.3)

To change one of the three features equals a complete series of formfinding experiments. To change all of them at once would end up in an exponential number of possible forms and variations i.e. sub forms.

Moving the highpoint position and to study the shift of form when the latter is approximating an edge is very exciting and particularly challenging in regard to the stress distribution. Much simpler however is the variation of the edge arrangement in terms of position and height of corner points and edge tension in relation to the high point while the high point is varied in height and dimension.

Last but not least and probably the most ample aspect of research is the list of masthead-geometries that could potentially be used as a feasible support for a membrane.

For a systematic modus operandi a step-by-step approach was chosen. Since the excessive amount of work of a total examination is falling aside of the scope of this thesis a limitation mainly to criterion 2, plus to a certain extent to criterion 3, was made.

A run through a set of experiments focussing on variable edge conditions together with shifting highpoint elevation is a barely manageable task not to mention the enormous data collection for subsequent interpretation.

That being said, more limitations need to be made. The primary goal of experiments with form-active structures e.g. tents is formfinding. Typically formfinding experiments are conducted using physical modelling or computational modelling i.e. digital simulation. Structural analysis or cutting patterning are advancements based on these preliminary steps, hence represent the production oriented phase of the overall workflow from draft to realization.

For the examination of the aforementioned form influencing parameters exclusively formfinding experiments were run through. Both traditional physical modelling and computational methods were used. The goal of the conducted experiments was firstly to increase the variety of forms and secondly making a visual assessment of the topographies generated through formfinding. The observation of curvature transformation in the course of successive deformation is a main focus of this first extensive series of experiments.

> *"In architecture and structural engineering 'form-finding' identifies the process of designing optimal structural shapes by using experimental tools and strategies, i.e. physical models to simulate a specific mechanical behaviour." (Tedeschi, 2014: 353)*

6.1. Formfinding

The concept of formfinding is common practice in tensile architecture i.e. form active structures. It describes a step in a process that typically comes before any engineering. However, the term is often misinterpreted for the idea of conceptual draft in architecture.

> Contrary to the action of drafting in architecture the procedure of formfinding is not referring to the creation of buildings, their visual appearance or functionality. While drafting is still an essential step in tensile architecture, the final shape i.e. the form of a building is only found through the process of formfinding. This process is driven by the selection and variation of the conditions for the genesis of form. Every form-active structure e.g. membrane lightweight building, requires one or several formfinding methods which feature the essential characteristics of a given type of construction. (Hoeller, 1999)

The concept of formfinding can be embraced as a method to determine the geometry of a structural system. Thereby the actual formfinding process is a dynamic performance of self-organisation of all forces within a structure until achieveing a state of equilibrium. Hence the geometry or so-called equilibrium form of a form-active structure is never drafted but always the result of a natural process.

A key factor to the outcome of the formfinding process is the physical environment. Every result represents the equilibrium form which has been established under the given conditions. As a consequence, the result of a form found geometry could only be rated after the complete set of form influencing conditions has been taken into account.

> However it is incomplete to reduce formfinding to a mere physical occurrence. Höller claims that true formfinding must include design intention and functional aspects as form influencing conditions. He insists on the point that there is not just one single i.e. correct solution for an equilibrium form. The term of formfinding as it is commonly used should be designated as form generation. (Hoeller, 1999)

The following chapters are a report on the strategies applied and the findings obtained.

6.2. Analogue methods vs. digital methods

Formfinding in general is done in by experimentation or simulation, i.e. physical or computational modelling. Several methods are known, which target different objectives and therefore yield to different outputs in both analogue and digital methods. In this sense, all methods have experimental characteristics in the way they necessitate the experimentation with boundary conditions.

6.2.1. Analogue methods

Formfinding with analogue methods is based on physical modelling. This comprises all traditional modelling techniques, which are common in architecture including a number of very specific techniques essentially used for modelling lightweight membrane structures. The global aim is to represent reality on a model scale.

One basic characteristic of analogue formfinding is the strictly material based approach. Be it a soap-film experiment, a rubber skin model or a cloth model of tulle or even linen; any result is essentially driven by material properties. The logic of material properties applied within given boundary conditions yet always finds a form, which is physically correct. It is the selection of materials that essentially determines the goal of an experiment. Physical models can deliver information on form, may enable measurements, show an architectural context or demonstrate a function i.e. mechanism. Hence models are intended to either be fromfinding models, measuring models, presentation models or mock-ups.

Physical models typically impart an unmatched three-dimensional experience. Convincing with haptic immediacy a model allows for intuitive rating of stress distribution. If a suitable cloth is used, light transmission i.e. shading can be studied. Within an architectural proposal the model is an unrivalled classic visualisation medium. Models still play the indispensable role of giving theory a live counterpart even for engineers that preferably work based on computer-based models. Nonetheless analogue findings have a limited validity. Physical models allow for little to no portability for subsequent processes. Particularly referring to engineering questions i.e. structural analysis or manufacturing e.g. confection it is very challenging to retrieve the necessary information from a physical model.

6.2.2. Digital methods

Computational formfinding methods offer an integrated way of modelling. A model is still the result of a computational process but other than the analogue model, a digital model allows quick changes in the boundary conditions and immediate access to subsequent analysis e.g. further engineering processes.

The big difference between digital and analogue form generation is the premise. Contrary to analogue methods computational formfinding does not necessarily involve material properties from the beginning since they do not influence the equilibrium equations in the analysis. A mathematical abstraction of reality makes for the numerical environment in which a formfinding experiment is performed.

Today a number of different simulation methods are known that are commonly used in commercial software suites. Several authors have thoroughly dealt with the evaluation of the various approaches that are implemented in professional formfinding tools. A scientific discussion among mathematicians is still active about the accuracy, the efficiency and the industrial relevance of computational formfinding methods.

> *„The previous decade has seen a surge of academic interest in and construction of bending-active hybrid structures. This has led to the emergence of numerous software environments which address questions on the form-finding and evaluation of bending-active structures.“ (Bauer, et al., 2018: 1)*

As to the purely experimental approach of the planned formfinding experiments within this thesis the production oriented features of available software are of minor importance. Nevertheless, it is crucial to understand, to what extent applications are capable to fluently model complex typologies. Commercial suites commonly feature a comparable form catalogue, which the software is able to calculate. State-of-the-art is hypars, any variation of saddle shapes, cones, arches etc. Even the solutions for non-trivial high point problems are often covered by default. To my knowledge no product can model a humped surface straightforward. Fortunately, more recent works in the field of dynamic relaxation have developed a strategy called particle spring systems, which allows for mesh generation i.e. mesh relaxation including almost arbitrary boundary conditions. For the envisioned digital formfinding experiments an application was set up within Rhinoceros 3D using the Grasshopper plug-in.

7. Traditional form finding

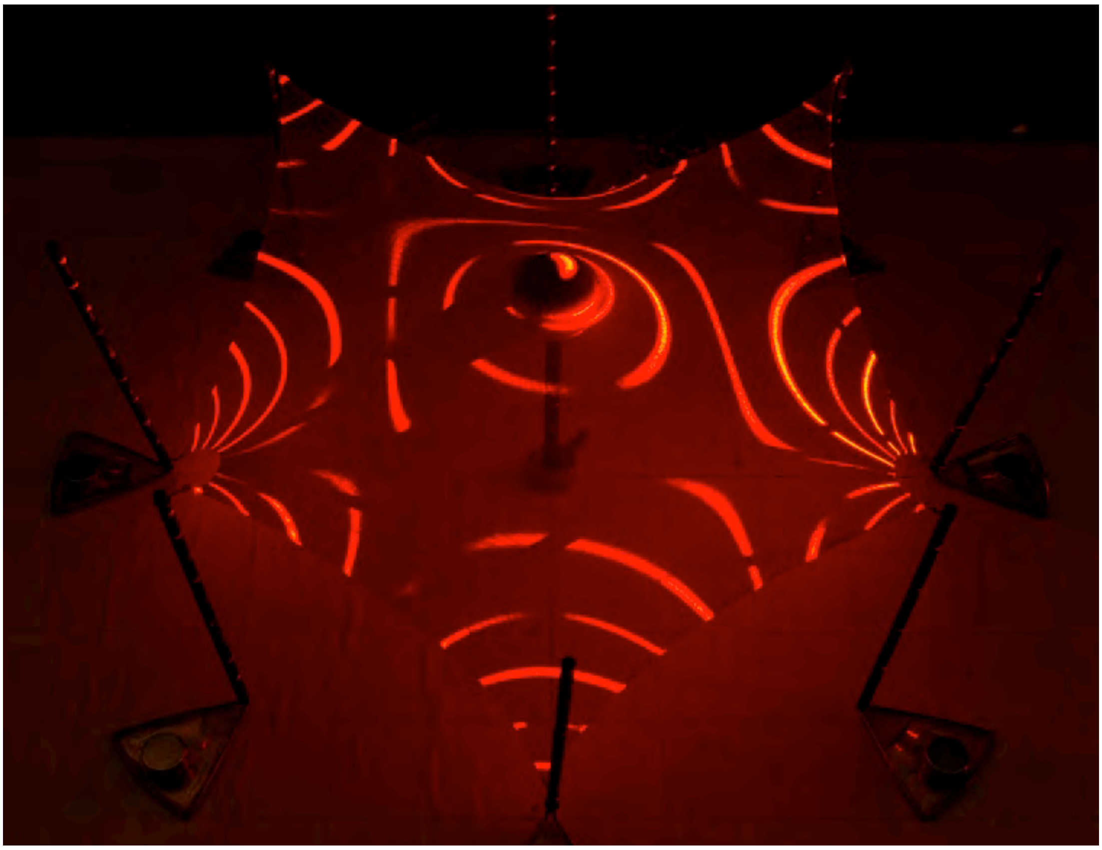

Figure 41: Laser contour lines on tulle

> *"Structures that transmit forces through axial compression or tension have an increased capacity to withstand loads with smaller cross sectional areas. Traditional form-finding strategy for axially loaded structures include: complex physical models, hanging chain networks, stretched fabrics, soap films etc. These techniques are difficult and time consuming. As a result, few designers investigated these form-finding potentials." (Tedeschi, 2014: 361)*

For the examination of humped surfaces an extensive series of essentially form generating experiments was planned. The primary goal was to compare basic shapes in various conditions of prestress and altering topography; in other words, to add an additional internal highpoint to a standard form and observe the shift of geometry in the course of deformation. Given the expected multitude of necessary iterations it is advisable to set up an apparatus in a way as to facilitate rapid and precise working. A technique is required which enables quick and straightforward changes of minor or greater impact. Changes are possible in layout, height of corner points along with height of masts i.e. supporting element, as well as the idem shape.

7.1. The physical model-building apparatus

7.1.1. Working plate

From earlier works a proven technology came into operation, which uses a coated steel sheet for the working plane and powerful neodymium magnets as anchoring elements.

For the steel sheet a piece of 750 x 600 x 3 mm (length x width x thickness) was chosen to comfortably accommodate a Ø 400 mm model. The steel sheet is coated with an inkjet paper upon which gridlines are printed like a drawing sheet. Four sheets of paper Din A3 are seamlessly glued upon the degreased steel sheet with quick drying mount spray.

The printed grid itself is metric with major grid lines every 50 mm and minor grid lines every 10 mm. If the models are at scale 1:20 the 50 mm separation of two major gridlines represent 1m.

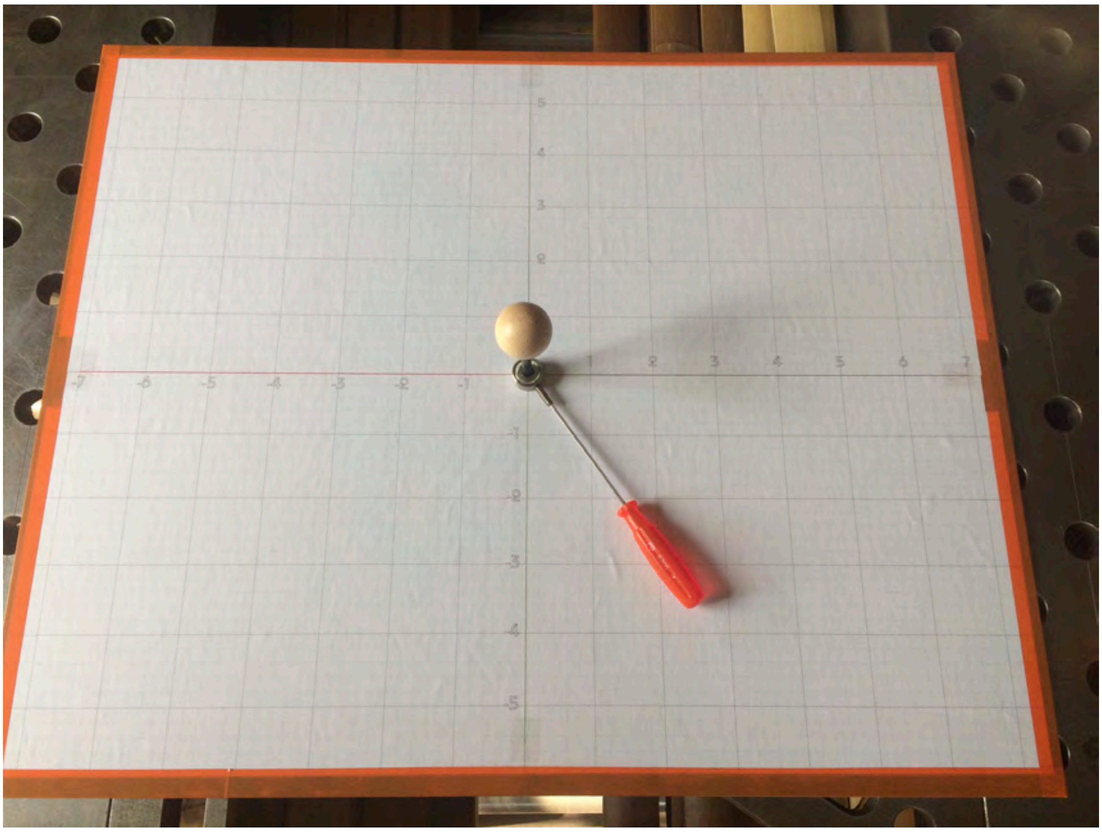

Figure 42: Working plate

7.1.2. Anchoring and guying

In general a model work plate has to provide proper features for fastening low points and highpoints. The steel plate allows for the use of neodymium magnets to strongly and securely hold any element being potentially used in a model in place. Pieces of fabric, the ends of thread or masts are common with membrane models.

On top of the paper layer, the powerful magnets can still be moved around easily by sliding from one position to the next. Lifting them off the surface however is hardly possible without a tool.

For the vertical adjustment of the corner points a universal column was developed. Pieces of carbon rods were installed on a base plate to work as a mobile column. The rods came from archery arrows shafts. These are small tubes made of lightweight but very resilient carbon fibre reinforced composite. To fix the rods in a vertical position on a base plate, bent brackets of stainless wire were glued upon a piece of polycarbonate sheet. The carbon tube can be slipped over the upstanding wire terminals of the bracket. In order to hold the whole column in place, again a magnet is placed upon the base plate to clamp it down to the working plane.

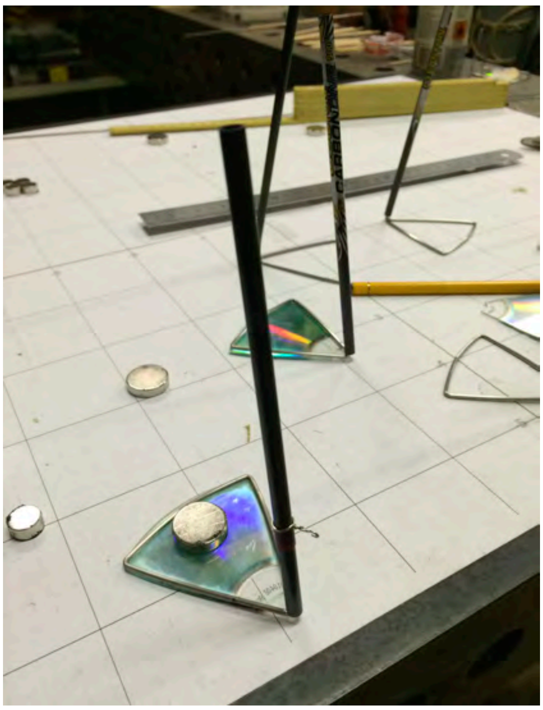

Figure 43: Column on base plate

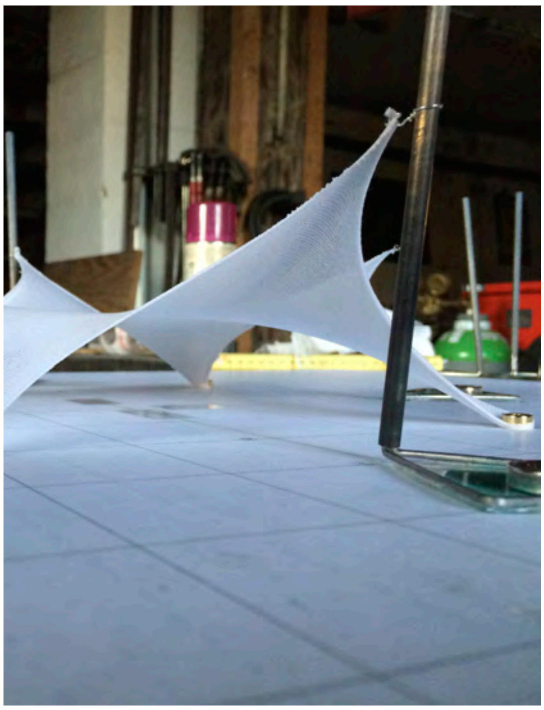

Figure 44: Membrane attachment

This first build unfortunately suffered from non-lasting glue joints. Due to the considerable forces acting on a membrane model all the wire brackets popped off the base plate within a short period of time. A second build for the latter consists of a stainless steel washer as base plate with a CDS welded stud on top. This provides both a reliable bond between column and base plate and a perfect fitting connector for the carbon rod.

A ring of very slim bent jewellery wire with a plied hook at the end can slide up and down the carbon rod. The corner of the membrane is clipped to that hook so that a corner point can easily be adjusted in height.

Some early models had low points directly attached to the plate with the magnet. In a later series the membrane edges were reinforced with an edge cable of fishing line running all around the model. This avoids excessive stress at the fabric corners and enables the control of edge tension. Pulling or releasing the edge line adjusts the prestress within the membrane. To control the tension of the edge lines, small reels are installed as a tensioning device.

The whole set up constitutes a versatile multi purpose installation. It is a modular concept with many possible extensions, which allows for the rapid creation of different shapes in numerous variations.

Figure 45: Tensioning device

7.1.3. Modelling materials

As stated before materials play a key role for the outcome when membranes are to be modelled. Their properties can be advantageous or they possibly represent a mere obstacle. For form finding experiments with membranes in general a material as flexible as possible is welcome. The flexibility, in turn, must be as uniform as possible i.e. isotropic, to prevent form finding from adverse drag. The ideal material in this regard is soap film. Soap films are known for the particular nature to always establish a minimal surface within possible boundary conditions; one, if not the major goal of every attempt to find a form. Soap films constitute the most accurate physical method to find not only an equilibrium of form but also an equilibrium of forces. Due to their impermanence and their lack of resilience, soap films are the least suitable material for deformation experiments.

With highpoint modelling a flexible material favours the expected elongations around the peaks. A first choice typically is stocking mesh, which is almost endlessly stretchable. Unfortunately, the knit does not allow for clean handling which makes stocking models very inaccurate.

Figure 46: High point with stocking knit

After a short test period, stocking knit was replaced by tulle. Hexagonal tulle is also isotropic but it is a lot stiffer than stocking knit. Tulle is a good compromise between flexibility and load capacity. All in all it is a versatile material and - most important - very forgiving in handling.

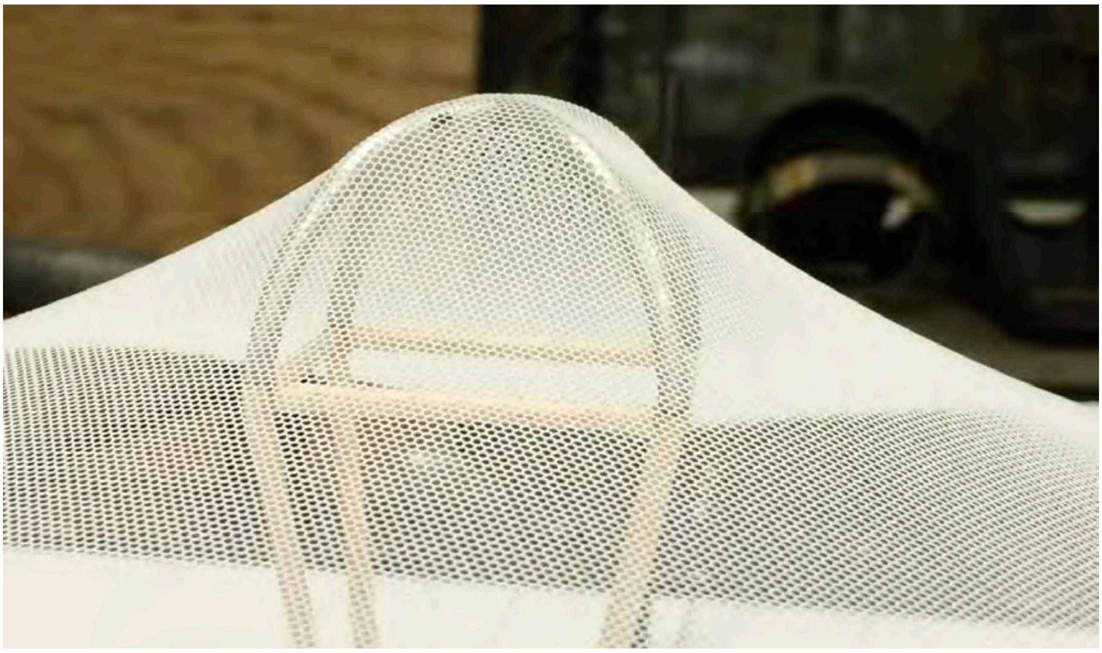

Figure 47: Hexagonal tulle after deformation

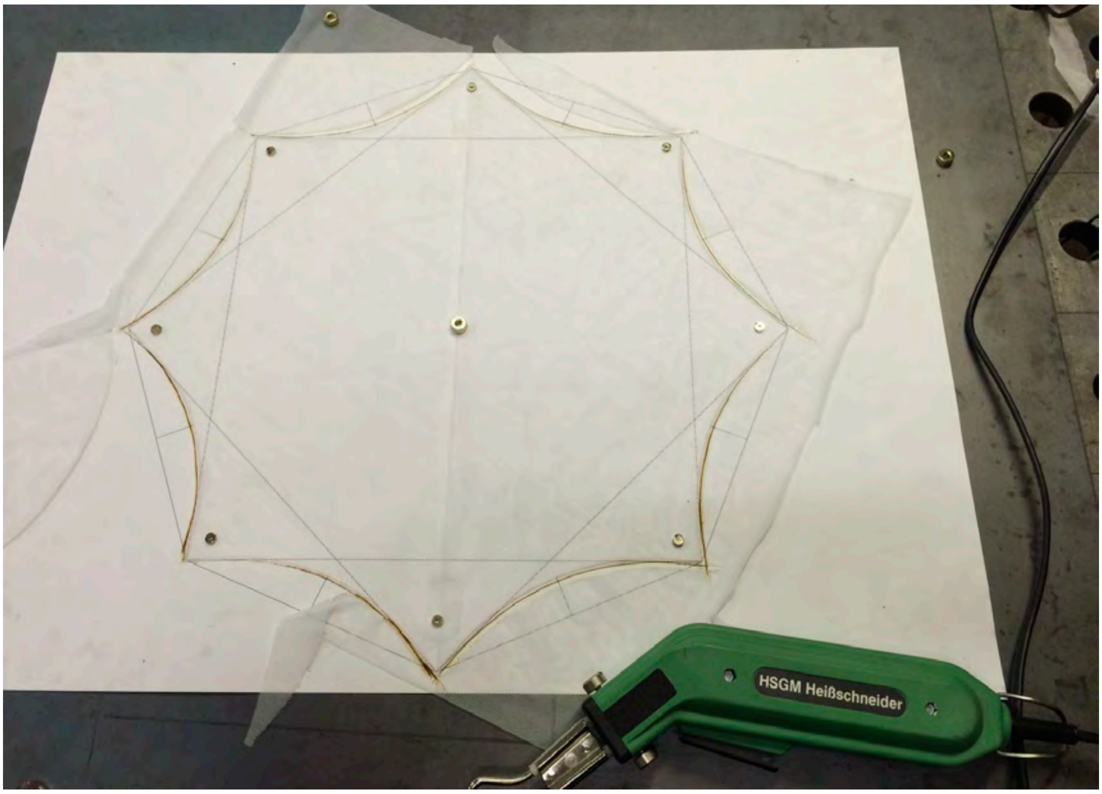

Figure 48: Cutting tulle with hot knife

The confection of tulle is easy. A print out on paper serves as a template. The cutting is done with good accuracy using a standard hot knife, which has the advantage of sealing the edges at the same time. For the patterns being used there is no compensation provided. Tulle requires very little prestress to take on form. The edges had a default sag of 10-15% and showed good behaviour for pre-stressing the membrane with and without additional edge reinforcement i.e. nylon lines. Edge lines are surprisingly easy to install if needed. A simple sewing needle can effortlessly be run through the mesh on the pre-stressed model. A huge advantage is the low friction between the nylon line and the tulle mesh. This allows for tying in a whole model in one or two circuits using the metal hooks at the masts as a grommet for the line and the tensioning reels as terminals. With little manipulation by hand the edge line tension distributes evenly along the borders.

A separate experiment was conducted with rubber skin. The material represents optimum isotropy, which results in beautiful, near minimal surface modelling. On top of that the closed surface allows for drawing orientation lines, which is interesting for highpoint examination. The vertical displacement of points on the membrane could be reproduced in equal measure as discussed in the works of F.O. (See chapter 5.1.).

Unfortunately, rubber skins need a considerable amount of prestress to find the proper form, which makes detailing a challenge. Solid corner fastening is one of several problems. The skin is very sensitive to perforation so that a simple hook or similar elements for corner fixation are not applicable here. All connectors were made as glue joints respectively with twin sided adhesive tape.

An additional complication with rubber skin lies within the border detail. To sufficiently prestress the membrane, it is necessary to create a good transfer of tension from two corners to the intermediate edge. All excessive material between two corners must be cut off with sufficient sag. An according reinforcement of the edge has to be found in order to effectively pull out the membrane in that area. Cables i.e. nylon line inside a pocket, are no option due to the friction between the materials. A doubling of the border with a strip of rubber however works satisfactorily. Iterations only identify the suitable amount of sag. Admittedly, this approach remains somewhat instinctive since measurements are not possible. Finally, the finding of correct edge sag for both rubber and tulle could not be concluded. The average percentage of sag with the realized models amounted to roughly 25% for rubber and to 15% for tulle.

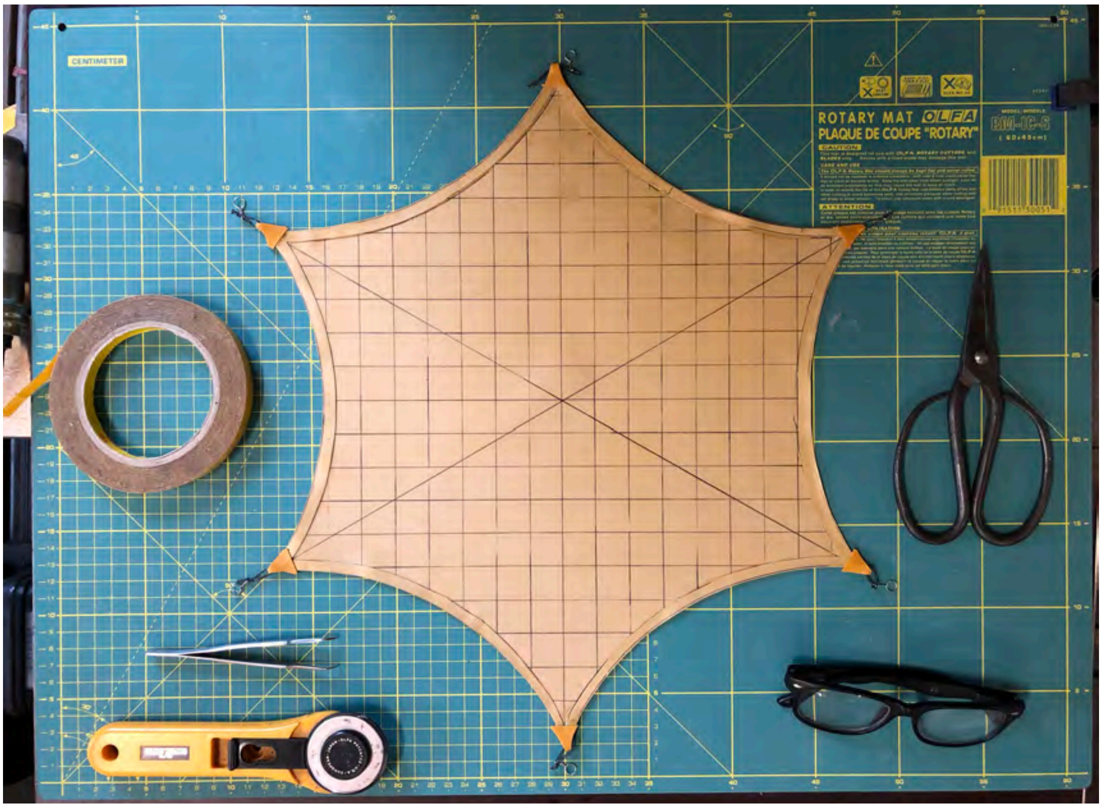

Figure 49: Confection of rubber skin

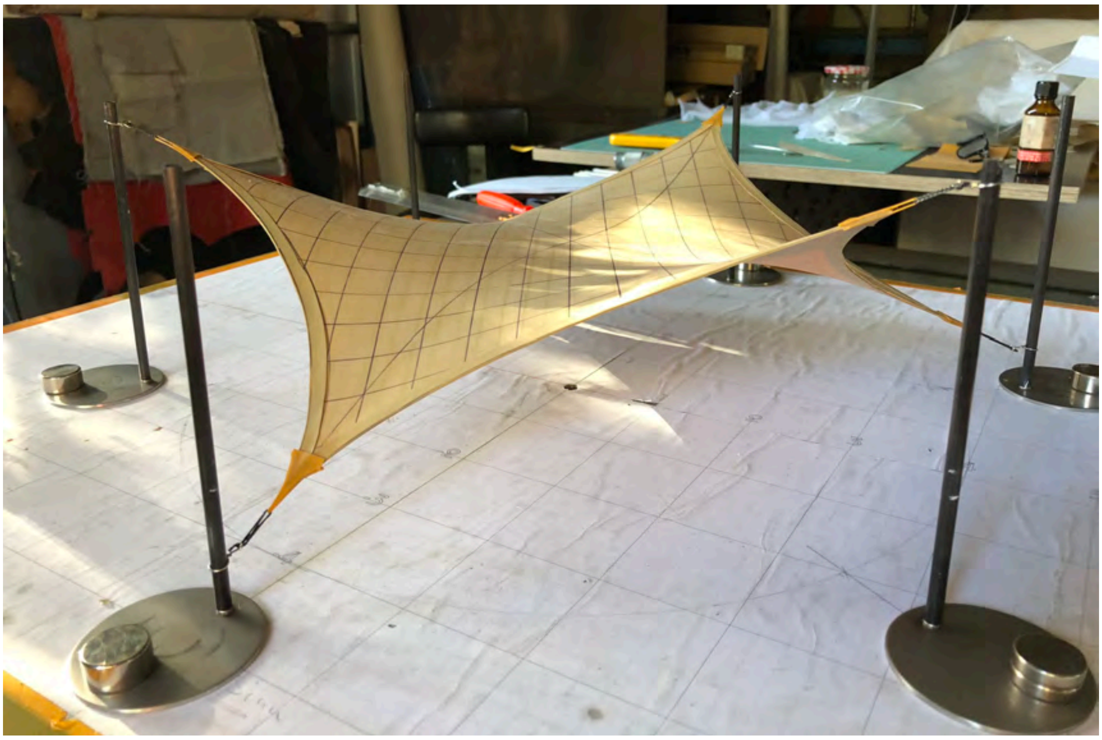

Figure 50: 6-P wave rubber skin membrane

7.2. Shapes

For reasons of standardization a universal envelope was chosen for all models. The margin is set to a circumscribing cylinder of Ø 400 mm x 200 mm height on the working plate. All forms are symmetric which means that all corner points are evenly distributed along a circular line with R=200 mm.

Various definitions of basic forms are possible. In a first step configurations with little to medium complexity were tested. These are 4, 6 or 8-point saddle shapes respectively wave tents. While each shape has the same extension in ground plan, the only modification for the corner points is made in z-axis.

Theoretically, an arbitrary shape can be chosen as input geometry to explore the altering geometry upon deformation. In his experiment however the restriction was made so that all starting geometries were either flat or a regular wave tent. In addition to this the high point creation is always in the centre of the membrane and perpendicular to the working plate. The only changes are made in size and elevation of the ram.

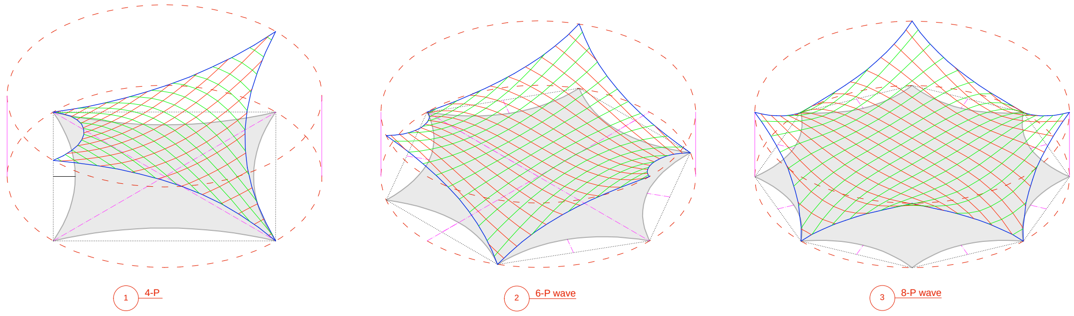

Figure 51: Model shapes, 4-P hypar, 6-P wave, 8-P wave

Three sizes of spheres are fixed on top of a central mast, which can be adjusted in height. The sizes are Ø 40mm, Ø 60mm, Ø 80mm.

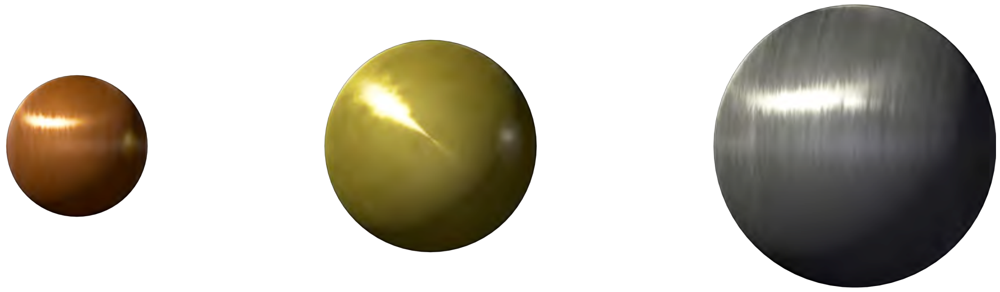

Figure 52: 3 Spheres 40 - 60 - 80 mm

Three levels of membrane deformation are run through with each of the spheres. The elevation steps are in relation to the radius of sphere. The increments are 50% of diameter each step up to 150% of diameter above the starting position. In case of the Ø 40mm sphere for example, the steps are 20mm, 40mm, and 60mm in z-direction above starting position.

The experiment was only concluded with the 6-P wave tent. Soon after the 4-P tent and the 8-P wave fell aside for the reason of unsuitable boundary conditions within the initial shape. In case of the 4-P sail one additional highpoint in the centre makes little sense because the saddle area already is ideally prestressed. The only results are adverse stress peaks between the low points and the hump and a subdivision into surfaces between the highpoints. The shape has some appeal and the geometry seems to have potential with one eccentric or multiple highpoints, which can be seen from the contour lines in the symmetric experiment.

In case of the 8-Point wave tent one major reason for exclusion is the large flat area in the centre. The topology of the cloth model basically consists of one mesh without subdivisions. Prestress typically is induced from the corner points. The wave effect of the corner point arrangement is enormously decreasing with the increasing number of circumscribing number of corner points. The higher the number of corner points, the closer the boundary is to a circular line which creates a completely flat surface. The deformation of a flat membrane with one central highpoint however can be studied with any circumscribing number of corner points.

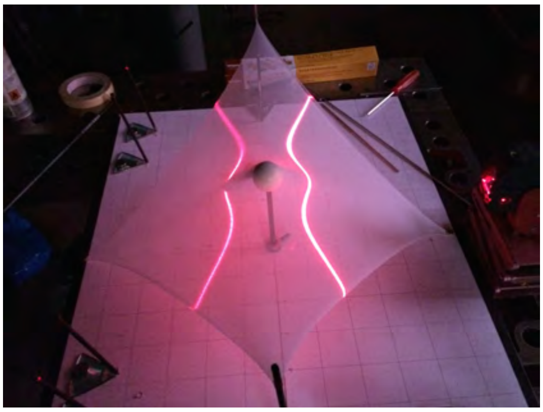

Figure 53: 4-point sail contour lines

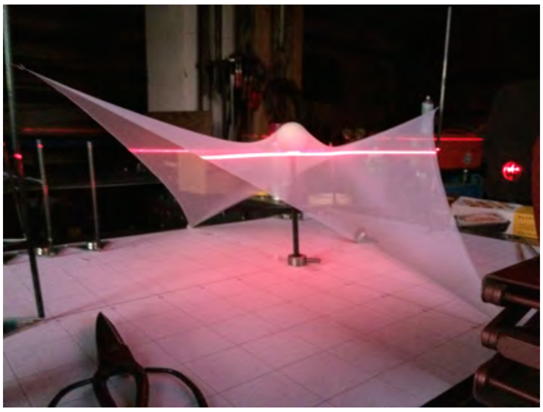

Figure 54: 4-point sail & Ø 40 sphere

A second reason for dropping the 8-point tent is the double symmetry axis of the structure. Basically, one central highpoint is creating the same geometry like in the case of a 4-point sail i.e. H-L-H or H-H-H. However for the reason of completeness a picture shall be added of the humped 4-point and 8-point wave.

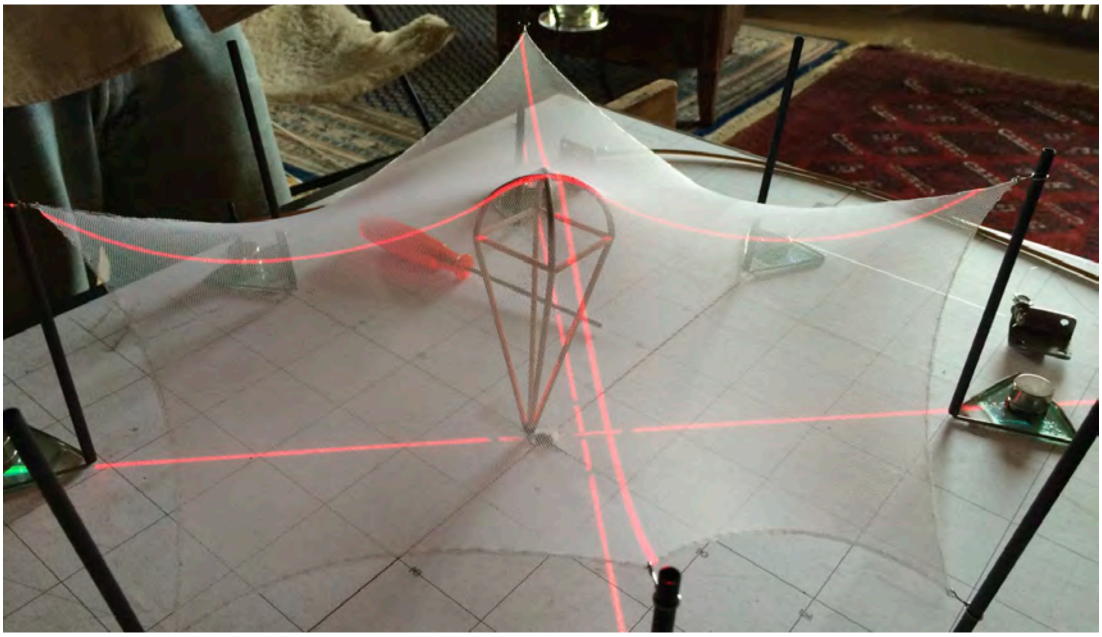

Figure 55: 8-point wave with laser lines

For playful form finding several other supporting elements than spheres were created. An arch made from a bent piece of wire or different trusses with a curved crown on top.

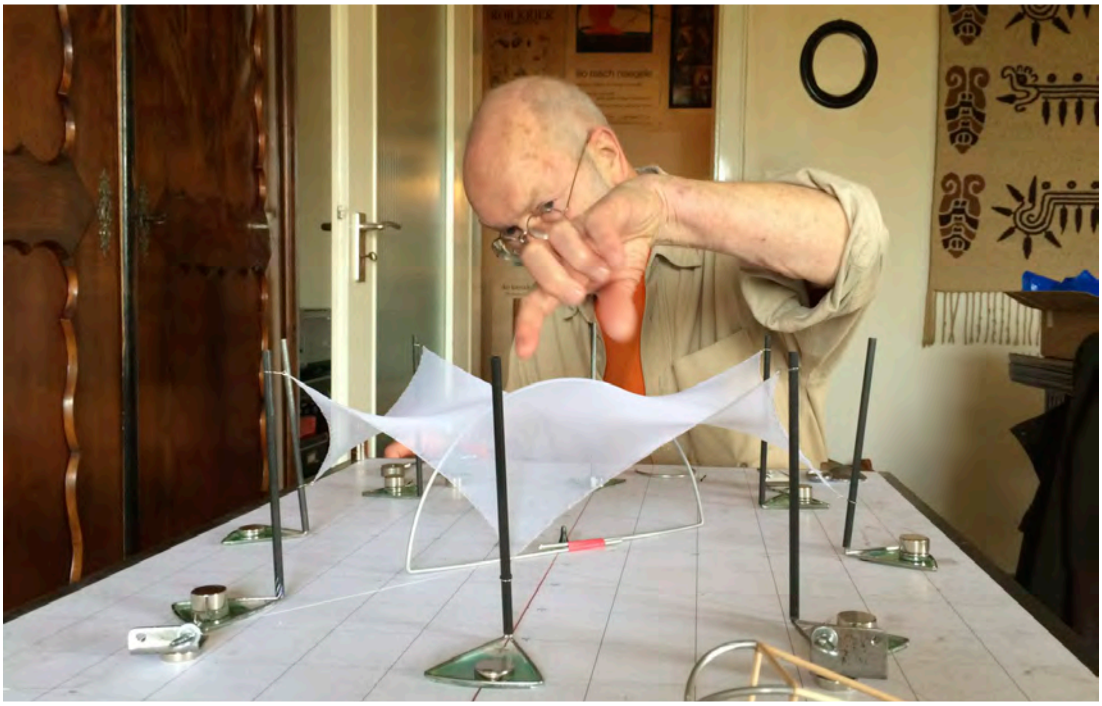

Figure 56: Arch supported tent. Discussion with Jürgen Hennicke

7.3. The 6-point wave

This paragraph shall give an overview over of the details of examination that were made on the subject of the 6-point model. Four configurations were run through and comparative measurements were made. Herein must be taken into account that this is about a form finding model, which does not satisfy the precision of a measuring model. In addition to this, the measurements are the result of a purely graphical translation, starting with a photography, which was processed in a CAD editor. Hence a lack of definition is causing certain vagueness as to the accuracy level.

Despite all this the observation of the gradual deformation allows for detecting clear trends. A comparison and a general evaluation of the behaviour of a membrane under deformation is the goal of the subsequent experiments.

7.3.1. 6-point flat

The flat configuration of this model is taken as a reference shape. The deformation is made to show the displacement of the membrane starting from a level position.

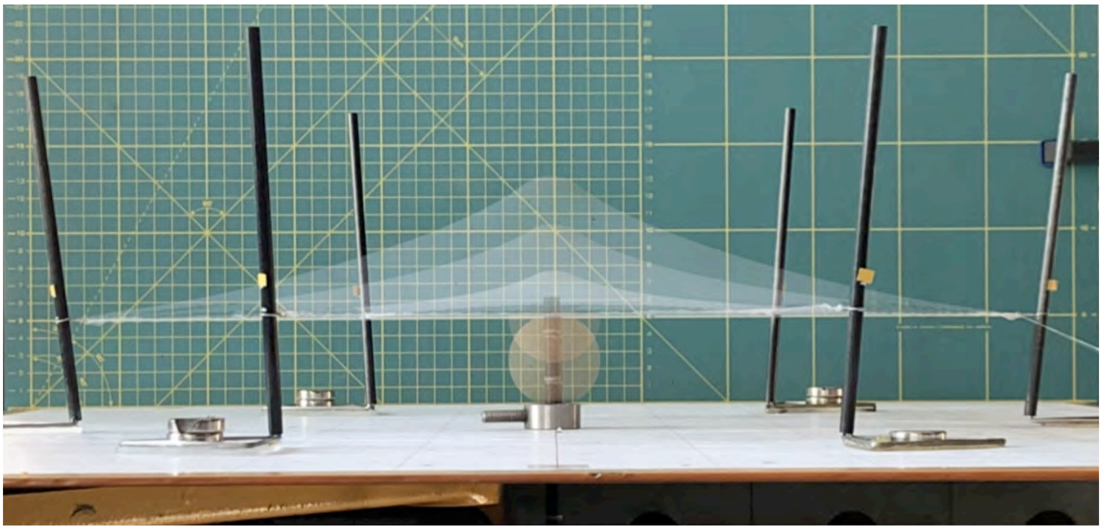

Figure 57: 6-P flat ø 40mm, deformation steps 0-3

Figure 57 shows the augmenting deformation as a sequence of step 0-3 in a quadruple multiple exposure. The support applied in this experiment is a ø 40 mm wooden sphere. The increments in z-direction are the aforesaid $_{+}$20mm each step, reaching from $_{+}$0 to a maximum of $_{+}$60mm.

Figure 58 shows the grade of deformation as a section from L-H-L. The coloured section lines outline the steps 1-3.

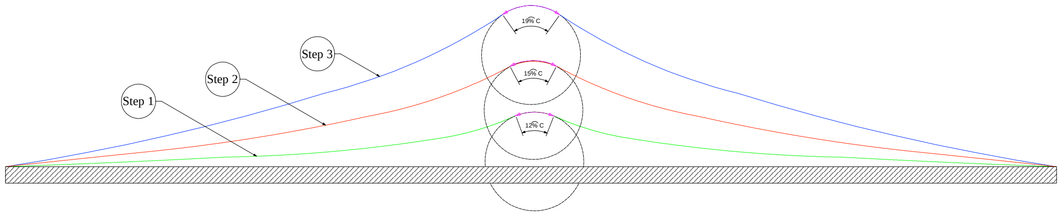

Figure 58: 6-P flat deformation sequence 0-3

Observations:

The deformations at step 1-3 are expectedly symmetrical. In a first step, the increase of the base area is 95%. Hence the most significant impact on the initial shape happens immediately upon the first deformation. The increments being +20mm each show a nonlinear increase of the area underneath the section line upon step 2 and 3.

6-P flat	**Sphere**		
Model Diameter	ø 40		
400	Verformung / Deformation		
Elevation	1	2	3
	50%	100%	150%
Level above 0.0	20mm	40mm	60mm
Base	0.0184	0.0184	0.0184
Area section	0.036	0.0612	0.0902
Total increase of area	0-1	0-2	0-3
	0.0176	0.0428	0.0718
	96%	70%	80%
Incremental increase of area	0-1	1-2	2-3
	0.0176	0.0252	0.029
	96%	70%	47%
Contact surface % of Circumference	12%	15%	19%
Impact on initial form	100%		

Table 7-1: 6-P flat deformation values

7.3.2. 6-point wave 40

More interesting for the study of deformation is the 6-point wave tent. Every section line automatically runs through the membrane from a low corner point to the central highpoint ending at a high corner point. Two cases of deformation can be studied at the same time.

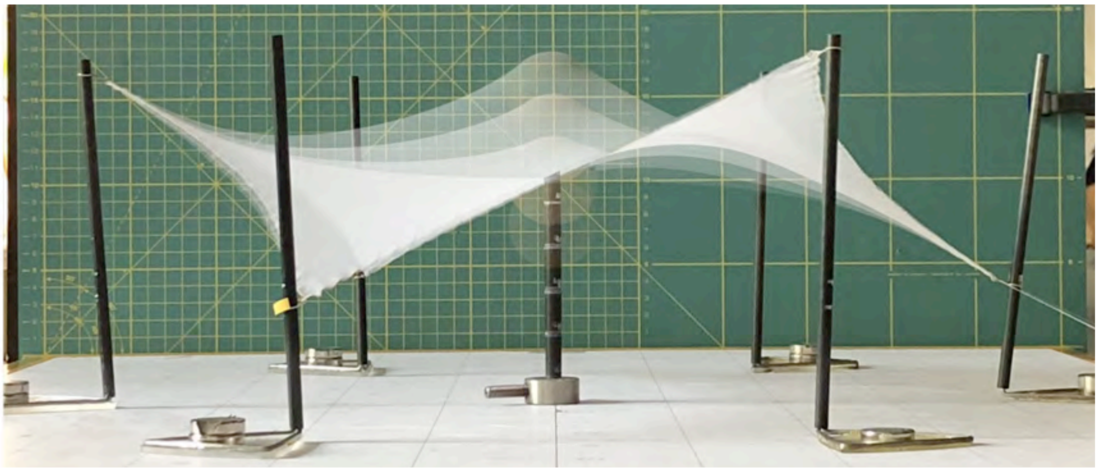

Figure 59: 6-P wave ø 40 mm, deformation steps 0-3

Figure 59 again shows the progressive deformation as a sequence of step 0-3 in a multiple exposure. The support applied in this case is a ø 40 mm sphere equalling 10% of the model diameter. Figure 60 shows the coloured sections of step 1 to step 3 from highpoint to highpoint to low point i.e. H-H-L. The circular line on top of the central highpoint represents the percentage of covered support surface at each stage. The green bottom line indicates the moment of complete pullout of the membrane from its original position as a ratio of total model length.

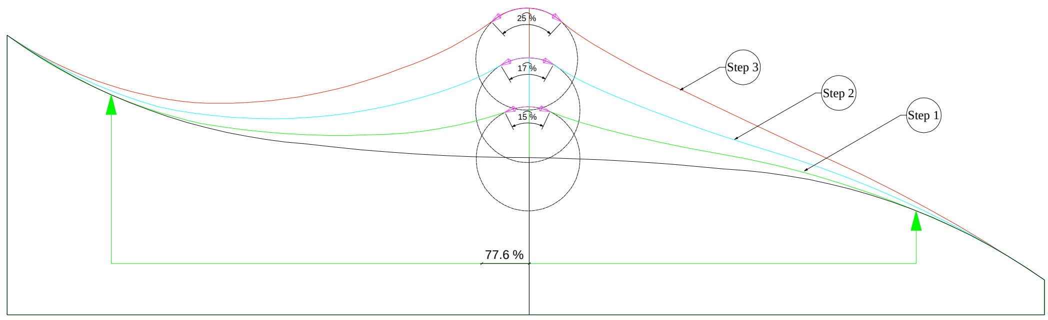

Figure 60: 6-P wave ø 40 deformation sequence 0-3

Observations:

The deformations on each side at step 1-3 are asymmetrical. The incremental areal increase upon each step however is close to linear 7% on the left side and 11% on the right side referring to the area below the section line. The total deformation amounts to 32.3% increase of overall area. The most significant impact on the initial shape occurs upon deformation in step two. The section line reaches a complete separation from the initial form and hence represents an all-new shape.

6-P wave	**Sphere**					
Model Diameter	ø 40					
400	Verformung / Deformation					
Elevation	1		2		3	
	50%		100%		150%	
Level above 0.0	20mm		40mm		60mm	
	Left side	Right side	Left side	Right side	Left side	Right side
Base	0.1024	0.0665	0.1024	0.0665	0.1024	0.0665
Area section	0.1091	0.0734	0.119	0.0825	0.1303	0.0931
Total increase of area	0-1		0-2		0-3	
	0.0067	0.0069	0.0166	0.0160	0.0279	0.0266
	7%	10%	16%	24%	27%	40%
Incremental increase of area	0-1		1-2		2-3	
	0.0067	0.0069	0.0099	0.0091	0.0113	0.0106
	7%	10%	8%	11%	9%	11%
Contact surface % of Circumference	15%		17%		25%	
Impact on initial form	78%		100%			

Table 7-2: 6-P wave ø 40 deformation values

7.3.3. 6-point wave 60

In a second experiment the same form was deformed with a larger ø 60 mm sphere, which equals 15% of model diameter.

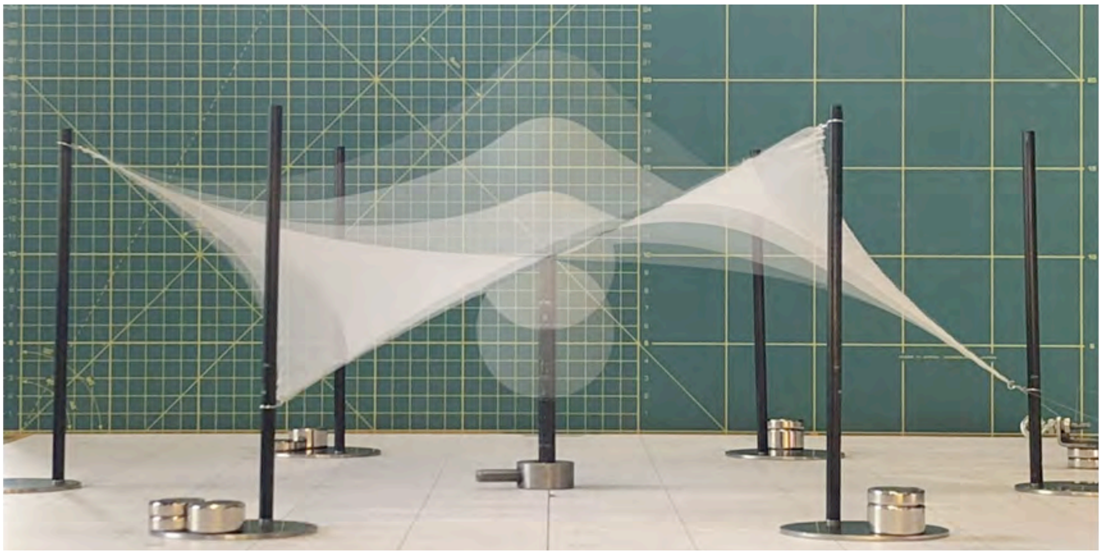

Figure 61: 6-P wave ø 60 mm, deformation steps 0-3

Figure 61 shows the progress of deformation from step 0-3. The elevation increments are 30mm each reaching a total 90mm above zeros. Figure 62 is showing the section line from H-H-L.

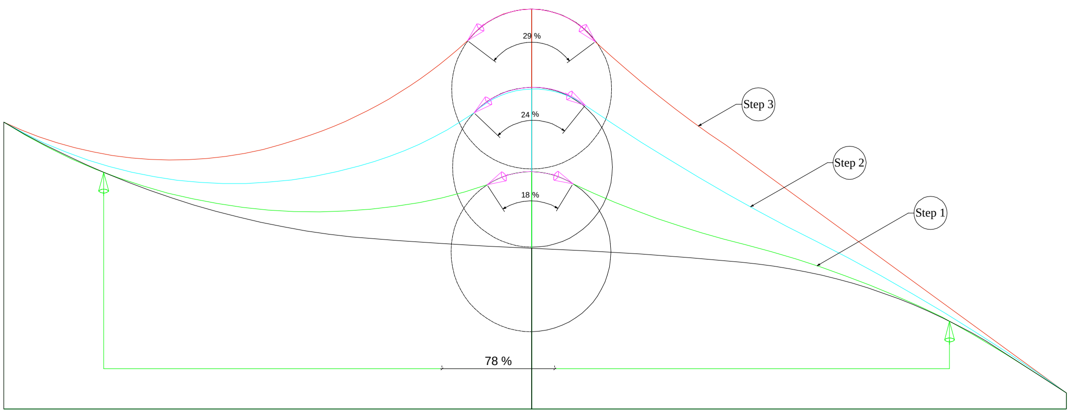

Figure 62: 6-P wave ø 60 deformation sequence 0-3

<u>Observations:</u>

The deformations at step 1-3 are asymmetrical on each side. The incremental areal increase upon each step is close to linear 13% on the left side and 17% on the right side referring to the area underneath the section line. One exception is represented in step 3 on the right side with 20%. The total deformation amounts to 57.7% increase of overall area. The most significant impact on the initial shape happens upon deformation step two. The section line reaches complete separation from the initial form. Another change of form is significant. Beyond the above-mentioned step 2 the right section line suddenly straightens between the low point and the highpoint edge, which means that all negative curvature of the initial form is tensioned out due to maximum stress near the support.

6-P wave	**Sphere**					
Model Diameter	ø 60					
400	Verformung / Deformation					
Elevation	1		2		3	
	50%		100%		150%	
Level above 0.0	30mm		60mm		90mm	
	Left side	Right side	Left side	Right side	Left side	Right side
Base	0.1202	0.0739	0.1202	0.0739	0.1202	0.0739
Area section	0.1331	0.0864	0.1534	0.1082	0.1763	0.1298
Total increase of area	0-1		0-2		0-3	
	0.0129	0.0125	0.0332	0.0343	0.0561	0.0559
	11%	17%	28%	46%	47%	76%
Incremental increase of area	0-1		1-2		2-3	
	0.0129	0.0125	0.0203	0.0218	0.0229	0.0216
	11%	17%	13%	20%	13%	17%
Contact surface % of Circumference	18%		24%		29%	
Impact on initial form	78%		100%			

Table 7-3: 6-P wave ø 60 deformation values

7.3.4. 6-point wave 80

In a third experiment the same form was deformed with the largest ø 80 mm sphere, which equals 20% of model diameter.

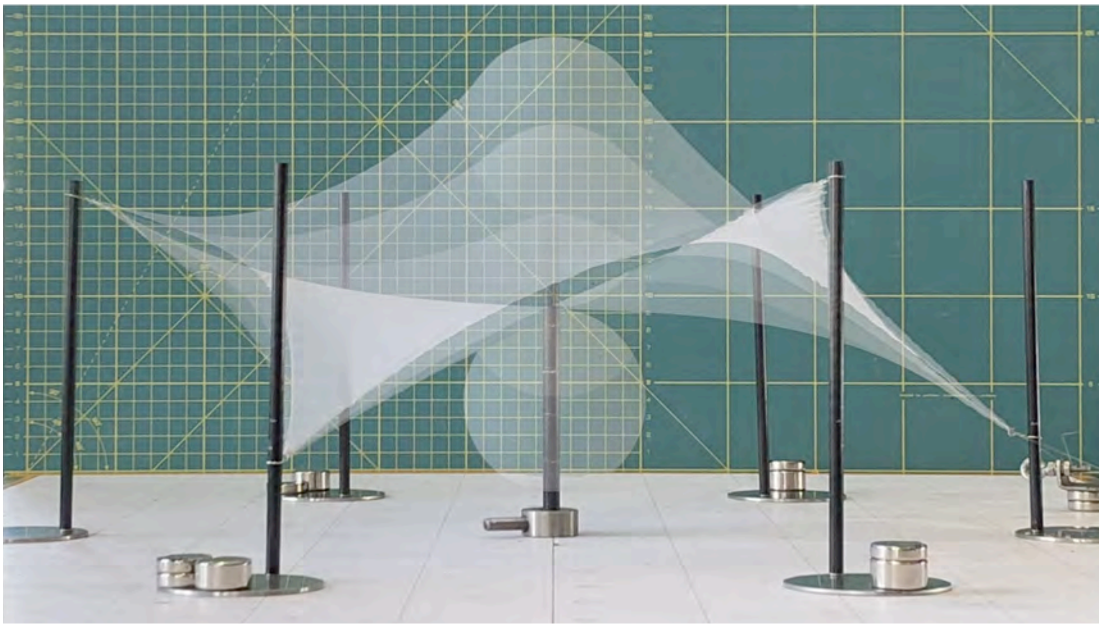

Figure 63: 6-P wave ø 80 mm, deformation steps 0-3

Figure 63 finally shows the progress of deformation from step 0-3. The elevation increments accordingly are 40mm each reaching a total 120mm above zeros. Figure 64 is showing the according section line from H-H-L.

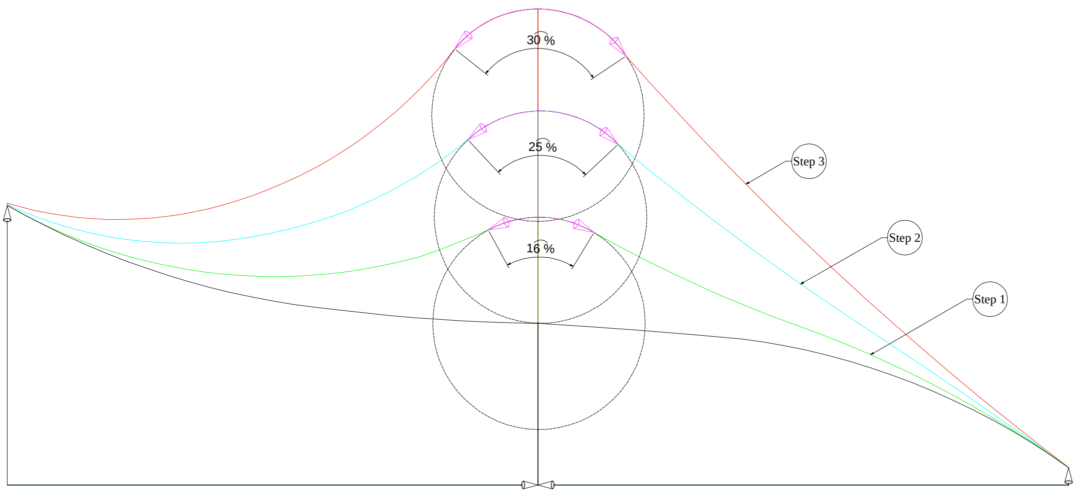

Figure 64: 6-P wave ø 80 deformation sequence 0-3

Observations:

The deformations at step 1-3 are asymmetrical on each side. The incremental areal increase upon each step is close to linear average 17% on the left side and 24% on the right side referring to the area below the section line. Exceptions are steps 1 & 2 on the right side with 20%. The total deformation amounts to 84.6% increase of overall area. The most significant impact on the initial shape occurs immediately upon deformation step one. The section line reaches complete separation from the initial form. Another change of form is significant. Beyond step 1 the right section line already straightens between the low point and the highpoint edge. Figure 63 also allows for the observation of deformation impact on the adjacent low points in the front. The heavy offset of the left edge line illustrates the strong impact of step 1.

6-P wave	**Sphere**					
Model Diameter	ø 80					
400	Verformung / Deformation					
Elevation	1		2		3	
	50%		100%		150%	
Level above 0.0	40mm		80mm		120mm	
	Left side	Right side	Left side	Right side	Left side	Right side
Base	0.1079	0.0655	0.1079	0.0655	0.1079	0.0655
Area section	0.127	0.085	0.1539	0.1116	0.1819	0.1382
Total increase of area	0-1		0-2		0-3	
	0.0191	0.0195	0.046	0.0461	0.074	0.0727
	18%	30%	43%	70%	69%	111%
Incremental increase of area	0-1		1-2		2-3	
	0.0191	0.0195	0.0269	0.0266	0.028	0.0266
	18%	30%	17%	24%	15%	19%
Contact surface % of Circumference	16%		25%		30%	
Impact on initial form	100%					

Table 7-4: 6-P wave ø 80 deformation values

Conclusion:

Four trends can be interpreted on the basis of the experiments with the 6-point wave membrane.

1. The relation between support and model size

   The ratio between the size of the support and the size of the model has a direct influence on the moment of pullout and maximum stress. Stress peaks occur sooner with higher size of support.

2. The distribution of areal shift between H-H and H-L

   The deformation rate between H-H is lower than the rate between H-L. The asymmetry is constant i.e. independent from the size of support.

3. The increase of covered area

   The areal growth below the membrane upon progressive deformation is almost linear.

8. Computational form finding

The goal of computational form finding within the experimental scope of this thesis is primarily to enable the same modelling as exercised with traditional modelling and secondly to enlarge the modelling features and eventually reducing the modelling process. As stated in the introduction, no commercial software is available in the field of tensile architecture which features the specific functionality of straightforward modelling internal highpoints i.e. humps of arbitrary shape and size. More recent form finding solutions in the field of digital simulation however allow for complex interaction between members such as textile and solids.

As discussed in the previous chapter about physical modelling, humping up a surface can be described as a gradual process of collision of a solid with a membrane. To translate this onward movement and the accompanying alteration of geometry into terms of computer-aided design, I introduce the term of contact modelling.

8.1. Rhino 3D and Grasshopper 3D

In the course of a discussion about the topic of this paper with my lecturer and supervisor Dr. Julian Lienhard, on how to establish a computational environment for contact modelling, the decision was made for an attempt within the Rhinoceros 3D®[4] Grasshopper 3D®[5] software package.

Rhinoceros3D® (abbr. Rhino, or Rhino 3D) is a full featured 3D and free form modelling CAD application which appears to be one of the most versatile and affordable tools in industry. Rhino is very popular in the field of industrial design, architecture, CAD-CAM, but also in rapid prototyping, 3D-printing and graphic design or jewellery.

The Rhino plug-in Grasshopper3D® (abbr. GH.) is a node-based graphical algorithm editor which is completely integrated within the Rhino command line. Grasshopper definitions are .gh files representing a generative algorithm, which interacts with objects within the Rhino-file. No scripting or programming skills are needed to

[4] Rhinoceros3D, Rhino, or Rhino3D is a CAD application software developed by Robert McNeel & Associates.

[5] Grasshopper3D is a visual programming language developed by David Rutten at Robert McNeel & Associates

create an algorithm with Grasshopper. The user is simply dragging components to the working pane called canvas. A component is representing a single step of a mathematical operation within a whole algorithm.

By connecting them in logic sequence and relating them to objects in Rhino the desired operation is being compiled. Components are organized in different categories and sub-categories, which appear in labelled component panels representing specific fields of operation. While many panels and their components stand for 3D geometry creation, many other algorithms can be created such as data flow management, automation, robots control etc. can be created.

In the short period of time since its first launch, Grasshopper has become the most popular and advanced algorithmic modelling tool. The Grasshopper3D® plug-in is an algorithmic modelling aid which enables advanced mesh manipulation and automation.

> *"Within a few years the plug-in gained a vast community of users and developers, including students, academics, and professionals. Grasshopper is available as a free download and it runs on a licensed copy of Rhinoceros 5.0 or higher." (Tedeschi, Wirz, & Fulvio, 2014: 33)*

8.2. Kangaroo - digital simulation

> *"Traditional form-finding techniques can now be digitally found using particle-spring systems that simulated the physical behaviour of deformable bodies. Originally developed for character animation and cloth simulation, particle-spring systems have emerged as a powerful technique for form finding. Whereas traditional techniques were difficult to apply, digital simulations allow designers to investigate form, in real time, by updating forces, supports and physical properties" (Tedeschi, Wirz, & Fulvio, 2014: 361)*

Among the numerous sets of available add-ons and extensions for Grasshopper, the most interesting for membrane simulation and contact modelling is the Kangaroo plug-in. Kangaroo is a physics based engine, which simulates a particle-springs system (PSS). Kangaroo, was developed by Daniel Piker[6], together with Robert

[6] Daniel Piker is a researcher on the frontier of the use of computation in the design and realization of complex forms and structures. workshops (including the AADRL, and a cluster at SmartGeometry) and presented his work at conferences around the world.

Cervellione and Giulio Piacento. The first release as a plug-in for Grasshopper was in 2010.

The use of PSS in structural form finding is a more recent approach among all known form finding strategies. Based on the numerical method of dynamic relaxation, the aim of a PSS is to find geometry of equilibrium forces i.e. minimal surface. The method consists in the discretization of the continuum structure into particles (masses at nodes) and connecting springs.

> *"Particle-spring systems are based on lumped masses, called particles, which are connected by linear elastic springs. Each spring is assigned a constant axial stiffness, an initial length, and a damping coefficient. Springs generate a force when displaced from their rest length. External forces can be applied to the particles, as in the case of gravitational acceleration." (Kilian & Ochsendorf, 2005: 2)*

For structural form finding PSS are commonly used to model compression only structures like grid shells. The basic configuration is the model of a catenary as a two-dimensional string of particles and springs. For membrane simulation a grid of particle-springs strings is used as to represent the three-dimensional structure of a sheet material. The main components are anchor points, particles, springs and forces.

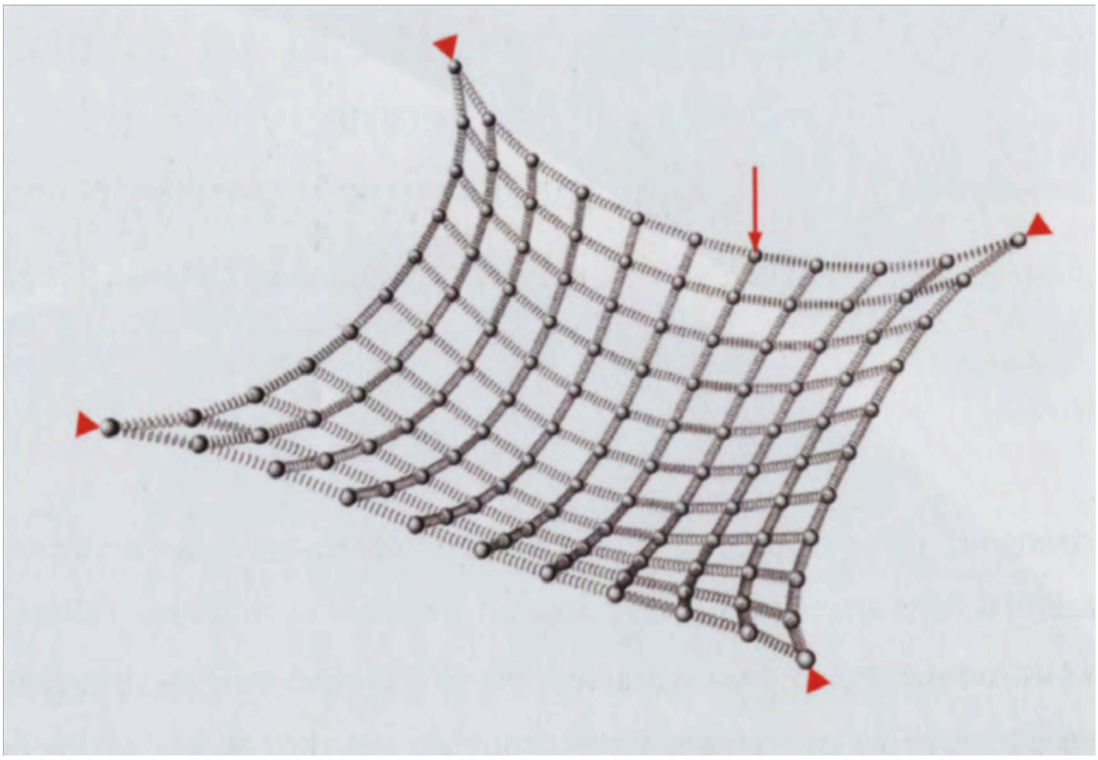

Figure 65: Particle-springs grid

„Once the simulation has stated, the particles move from their initial position until they reach an equilibrium state, which is dependent on the initial geometry, the force vectors, and the springs' defined properties. In accordance with Hooke's law, the lower the stiffness or k value the greater the spring elongation. Since particle-springs in this system behave like hinges without capacity to resist moment forces, equilibrium solutions carry defined loads exclusively through axial forces. This is the ideal condition for form-finding strategies." (Tedeschi, Wirz, & Fulvio, 2014: 362)

Most interesting about the above mentioned nature of PSS-form-finding is the analogy to physical modelling. The interactivity of the systems allows for immediate response to the designers manipulations. Every smallest change of boundary condition or stiffness values will cause instant and vivid reaction all over the system.

With Kangaroo 2 a number of additional components are included for the simulation of special mesh manipulation. For the experiments with humped surfaces the essential feature is the possibility to collide a mesh with a solid (contact modelling). The behaviour of the PSS-represented membrane within Kangaroo is similar to a thrown object impacting upon a curtain. It is possible to push a solid of any geometry into a membrane and then to observe it's rebound and to watch the transient oscillation of the cloth to its end position i.e. equilibrium form after impact. The whole simulation has a lot of natural appeal and doubtlessly is playful to conduct.

Figure 66: Particle spring

"Finding structural form using particle-spring systems has a number of advantages. Most importantly, the user can change form and forces in real time while the solution is still emerging. The environment educates the user as to the effects of forces on the form of structures and provides an interactive form-finding environment that was previously limited to physical models. By nature of the solution procedure, the particle-spring system always finds a possible load path for which the forces are in equilibrium. If no equilibrium solution exists, as in the case of an unsupported structure, then the masses will continue to translate in space until the user intervenes. The primary improvement over existing finite element methods is that this environment is fully dynamic, allowing the accurate computation of large displacements, velocities, and accelerations for the design of structural systems. The improvement over existing relaxation methods is that the design environment is fully interactive and dynamic, allowing the user to invent forms rather than analyzing existing forms." (Kilian & Ochsendorf, 2005: 5)

9. The toengi-mesh-machine

The toengi-mesh-machine (TMM) is the working title for the experimental form finding environment that has been set up within the Rhino-GH ecosystem. Looking back at the time and effort invested on traditional form finding using analogue methods, the new approach promised a much greater output in far less time. This assumption however turned out to be an illusion. Establishing the running system for regular use alone, was demanding and time devouring. On top of that a much broader set of experiments had been envisioned. Once the system was running with smooth flow a set of over 350 experiments was conducted within 3 weeks time. Several dozens of additional experiments were made under non-regular conditions e.g. with exotic membrane shapes or supports.

9.1. Test arrangement

Opposite to the rules with physical modelling all geometries from 3-point to 8-point membranes are explored. The list of shapes starts with planar polygons such as a triangle and ends with an octagon. In addition to this, every polygon is configured with several highpoint to low point arrangements. A 5-point sail for example happens to emerge in 9 different constellations with according names. Yet all shapes are strictly limited to the same envelope like the analogue models, being ø 400mm extension and 200mm height. Figure 67 is an overview over the panel of shapes in ground view. Figure 68 is an extract in perspective to display the three-dimensional appearance. The red contour lines allow for illustrating the examination intent. The variations of basic shapes with different topographies are going to be observed after introducing an additional highpoint. Again the test arrangement includes one collider in central position and vertical motion only. Colliders however were not exactly the same as in the physical models. The sphere experiments comprise a series of tests with ø 40mm, ø 80mm and ø 120mm. Each of the colliders is moved upwards into the membrane from 50% of its diameter up to a maximum of 150%.

As stated before, the membrane simulation is extremely inspiring and somewhat addictive. For pure curiosity a number of exotic collider shapes were created to interact with the membrane either in irregular or multiple positions and non-vertical motion. For methodical reasons, these results are left to the discussion.

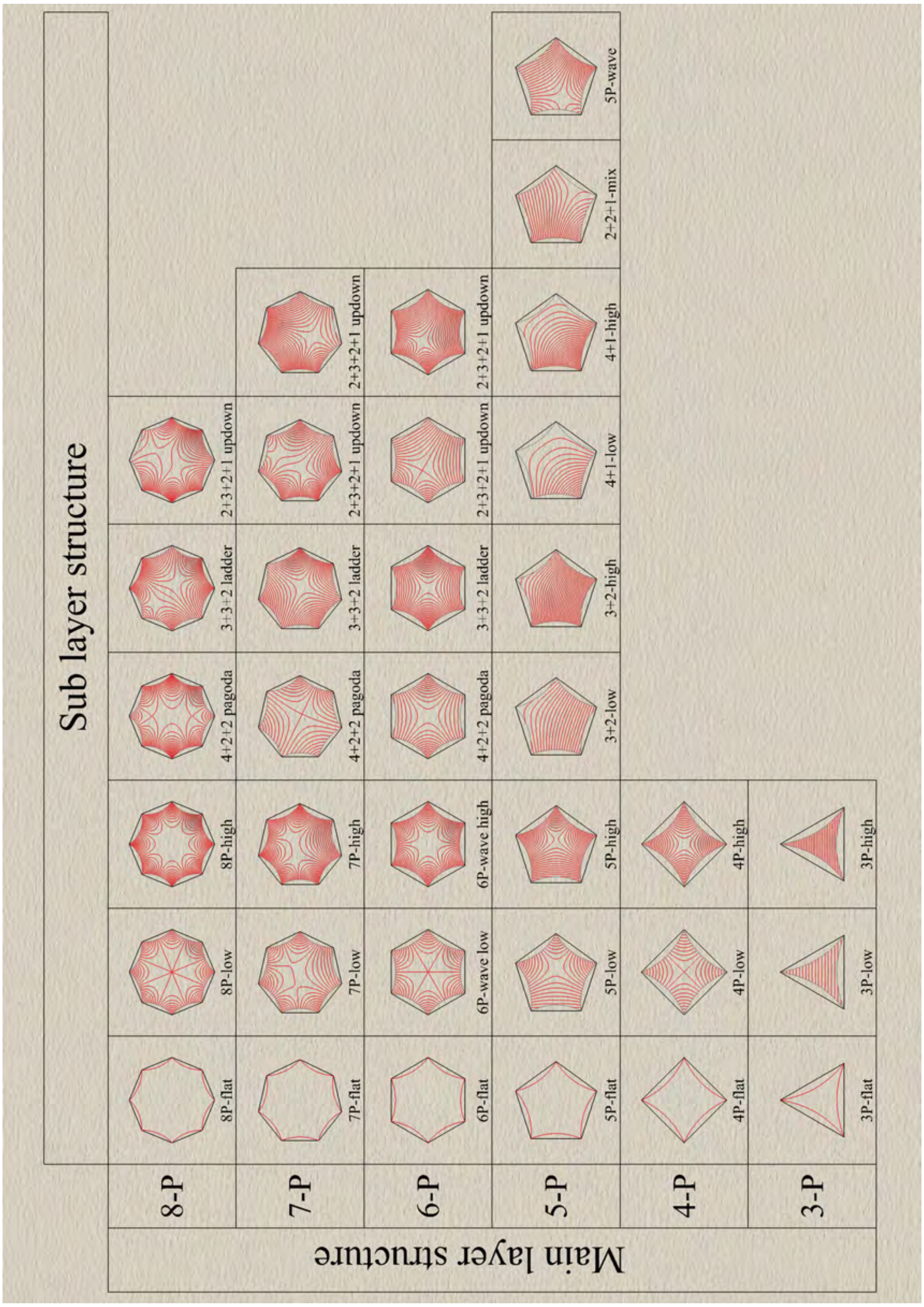

Figure 67: TMM-panel of shapes

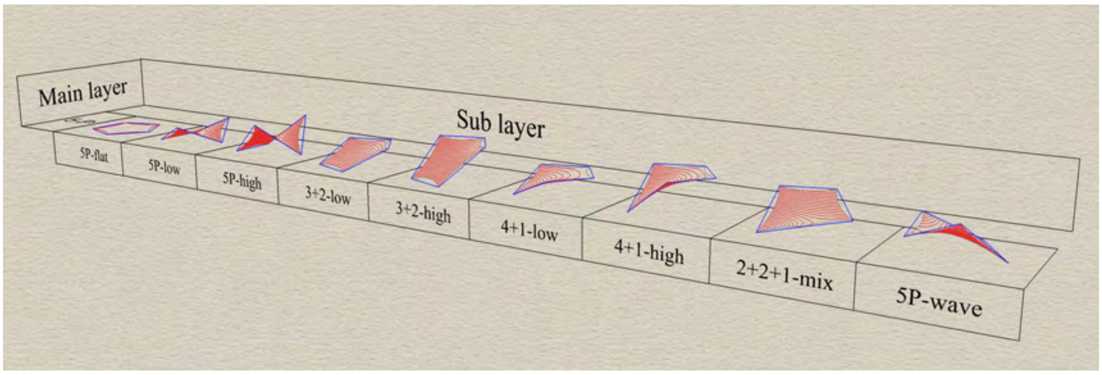

Figure 68: TMM-panel of layer 5P

9.2. Settings in Rhino

As illustrated above the Rhino file has to feature a suitable layer and sub layer tree in order to facilitate a distinct breakdown. Primarily the main layers are named referring to the basic geometry meaning 3-points, 4-points etc. The list of possible planar polygons starts with a triangle and ends with an octagon.

A required number of sub layers is imbedded within each main layer to store the configuration i.e. variation of the basic geometry. These geometries are basically the edge-lines of the input curve for the mesh generation within Kangaroo (fig. 69). Each sub layer has an explicit name that is conform to a consistent nomenclature. Other than displayed in figure 68 all sub layers are named for example 5P followed by a hyphen and the detailed name.

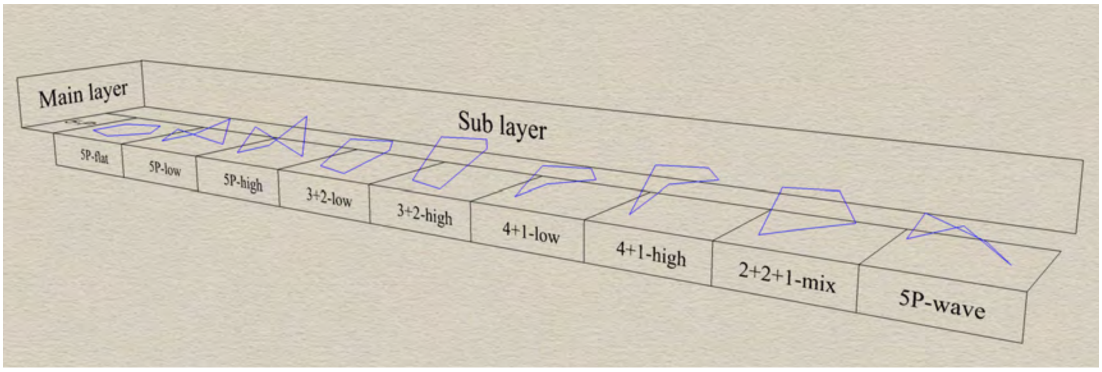

Figure 69: TMM-panel of input curves layer 5P

A second tree of layers is necessary to sort all collider geometries. One main layer is providing the path to all the featured solids that are stored in according sub layers. This determined layer tree is decisive not only for the data flow between rhino and grasshopper but also for the subsequent storage of the formfinding results. Every accomplished form will be baked to the originating layer and sub layer within the Rhino file.

9.3. GH definition

The workflow within GH definition comprises data management tasks and a number of calculation steps. Schematically it can be described as a sequence of the steps illustrated in figure 70. The chart however does not mention the data filter that is needed to filter the results before baking.

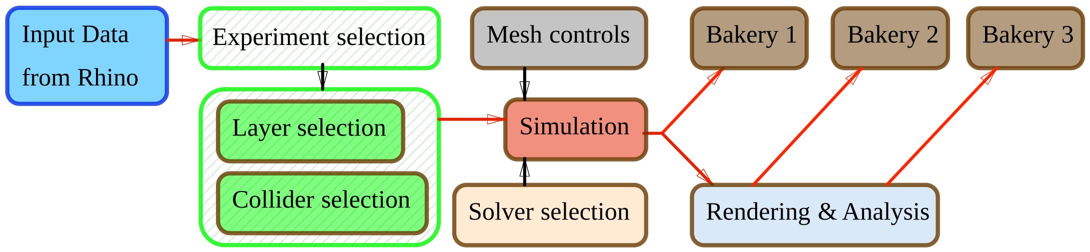

Figure 70: TMM GH work flow

To give an overview over the whole GH-definition with good resolution is impossible within the print size of this paper. It resembles more a road map than a detailed close up of all the features.

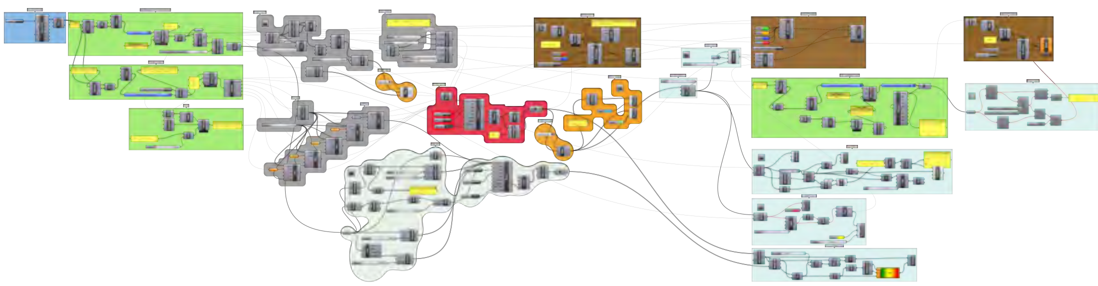

Figure 71: TMM GH-definition

- Data collection – blue
- Data flow – green
- Controls - grey
- Simulation (Kangaroo) – red or light blue
- Bakeries - brown
- Analysis - light blue
- Options - orange

For reasons of agreement among the authors the details of the TMM GH-definition are not published within this thesis. However the file is available upon request to all interested researchers for non-commercial use. This definition dates to 2016. Due to the on-going evolution of Grasshopper by a vivid user community it has partially become obsolete in the meantime.

9.4. Shaping

To kick off with the digital modelling it was interesting to see how much different the hypothetic mesh reacts upon deformation. At least one comparison was made with a section through a 6P wave tent with ø 80mm collider.

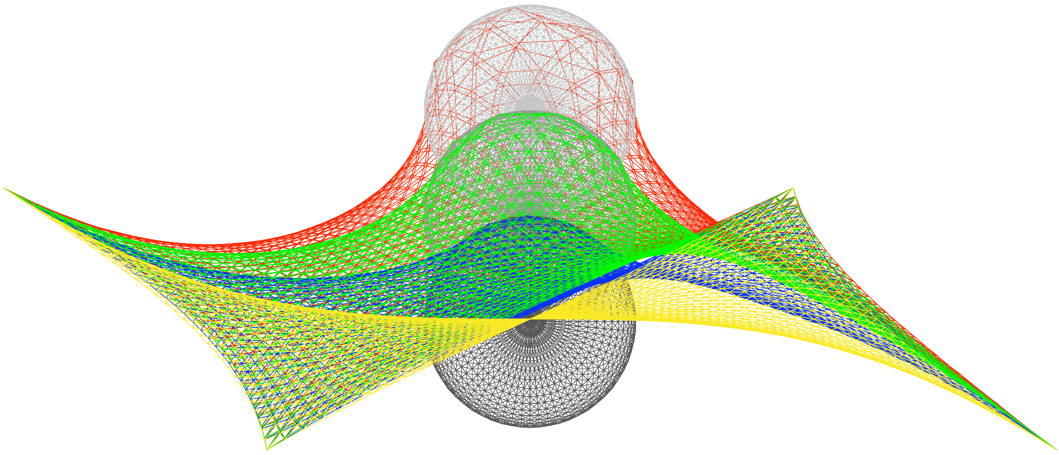

Figure 72: Section H-H-L 6P wave low 80

Three things can be observed at first sight.

1. The membrane behaves roughly the same like in the physical model. The lifting increments upon elevation 1+2 are regular.

2. Exception elevation 3. The membrane is loosing tension and seems to drip off the sphere.

3. The mesh size over the sphere is growing with increasing height of collision, which indicates excessive stress at the transition from unsupported to the supported area.

The overall impression is that the digital mesh has a beautiful form with pronounced yet naturally smooth curvature. The fact that the augmentation of space below the membrane upon the gradual deformation is similar to the observations with the physical model is a good proof for deformation behaviour in general. By visual assessment the stiffness difference between the more flexible Kangaroo mesh and the tulle mesh used for physical modelling can be distinguished. The area of transition between supported to unsupported membrane is characterized by slightly more buckling in case of the digital mesh. The phenomenon can already be observed upon the first step of deformation and not only between steps two and three, where the buckling is pronounced. The phenomenon however of altering mesh width in certain areas can firstly be understood as the occurrence of local stress peaks and secondly as a result of stiffness settings within the numerical environment. Typically the mesh behaves unobtrusive up to medium deformation level i.e. 100 % collider elevation. Beyond that the increase of stress above the collider is abrupt.

In the conducted experiments the goal was to achieve maximum feasible deformation hence the stiffness values were set as low as possible. Even if the settings were not properly determined the mesh behaviour can roughly be described as the representation of an extremely elastic rubber skin. An extension of the GH-definition with a different solver allowed for the for soap film simulation. The deformation showed almost identical results in terms of formfinding, except the maximum possible collider elevation in general was limited to less than 100% and the procedure i.e. deformation sequence was far more sensitive to mesh collapse. To achieve the next level of deformation small lifting increments were necessary to prevent the mesh from bursting.

Two very interesting features of the TMM for visual assessment are the possibilities to display the contour lines of the membrane topography and the so-called contact line between collider and unsupported membrane. While the former is an excellent feature for the observation of surface evolution, the latter allows for the precise observation of the collider geometry and its impact on the membrane in the course of proceeding deformation.

Contrary to the assumption of a mere ring element in case of a spherical collider, which is a common simplification within standard software, contact modelling allows for a much more accurate mapping of the true impact angle between the membrane and the supporting element. In case of spherical colliders with a membrane of uneven height of corner points, the contact line adopts a twisted shape. The twist itself is depending on the amplitude of corner points in z-axis. Likewise in case of asymmetrical i.e. freeform colliders, the contact line takes a shape, which maps the collider surface area affected by the adjacent membrane. It is controlled by the factors of local collider radius, height of collider and encircling boundary conditions.

For the illustration of the curvature evolution upon deformation, a selection of cases from the standard experiments is graphically processed in renderings.

9.4.1. 3P-flat

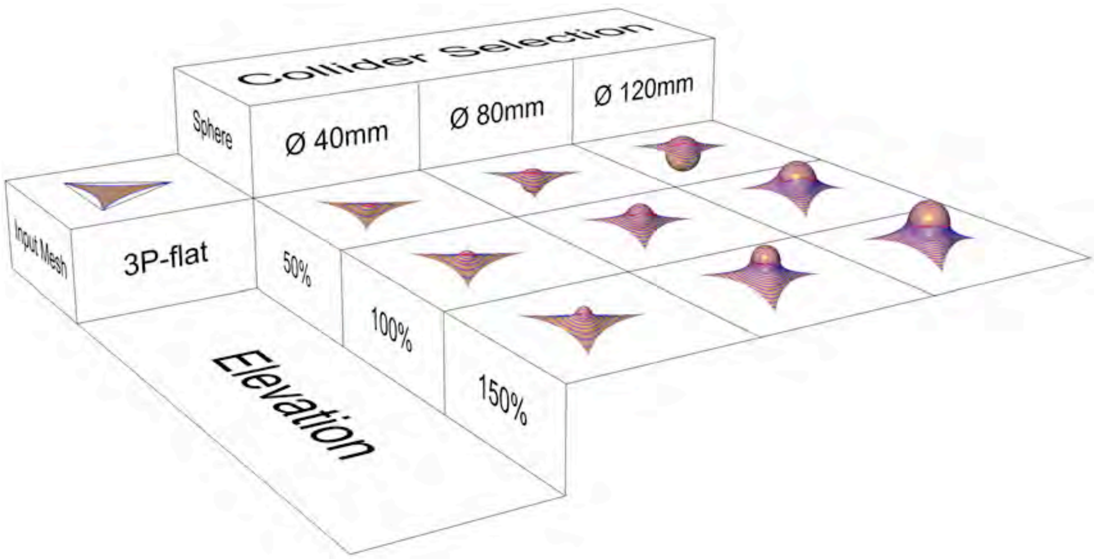

Figure 73: Form evolution 3P-flat

Typically a three-point surface is always flat. As soon as one edge is curved or an internal highpoint is added, the surface becomes a membrane with double curvature. The case of 3P-flat is ideal for several general observations. The level arrangement of the corner points ensures a regular deformation, which applies for all flat input meshes.

A regular twist is curving the contact line (red), which corresponds to the order of edges and corners of the membrane. The lower the number of corner points, the stronger the twist of the contact line. In the areas between collider and adjacent corner the line is lifted, in vicinity to the edges the contact line is lapsing (fig. 74).

Typically the point of expected burst of the mesh is closely related with the contact line approximating a more or less equatorial compass on the collider sphere. This moment could not be systematically assigned to a precise elevation throughout all experiments. Due to minor adjustments e.g. inconsistent elevation increments, the meshes behaved slightly unequally. A distinct relation however can be found between collider sizes and mesh size. In general the maximum extent of the contact line with the ø 40mm sphere is reached beyond 150% elevation. The ø 80mm sphere normally reaches its maximum extent at exactly 150% and the ø 120mm sphere generally at 135%.

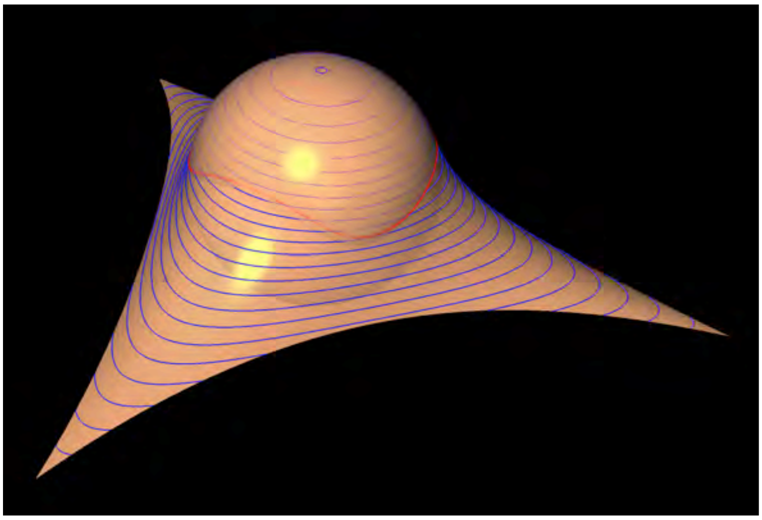

Figure 74: 3P-flat, ø 120-02

9.4.2. 3P-high

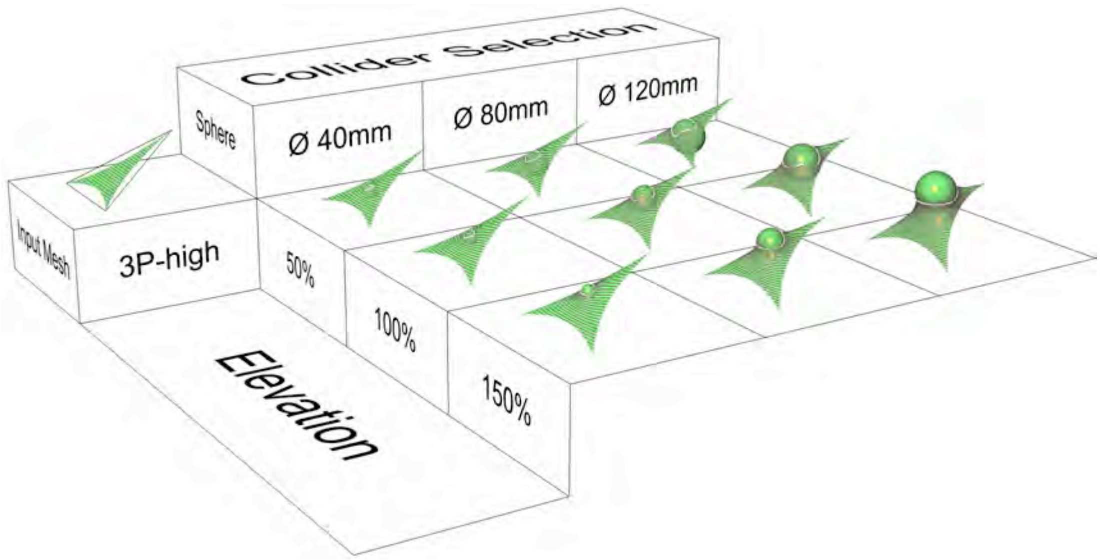

Figure 75: Form evolution 3P-high

The case of 3P-high covers an additional complication, which occurs with inclined surfaces. Due to the inclination the collision of the sphere upon the membrane is no longer perpendicular. This creates a downhill side and an uphill side of deformation. The characteristic deformation, which was documented in case 3P-flat persists, but it morphs into an alleviated downhill slope and a very accentuated uphill saddle. The observation of the contact line (white) reveals a strong twist particularly upon 100% and 150% elevation.

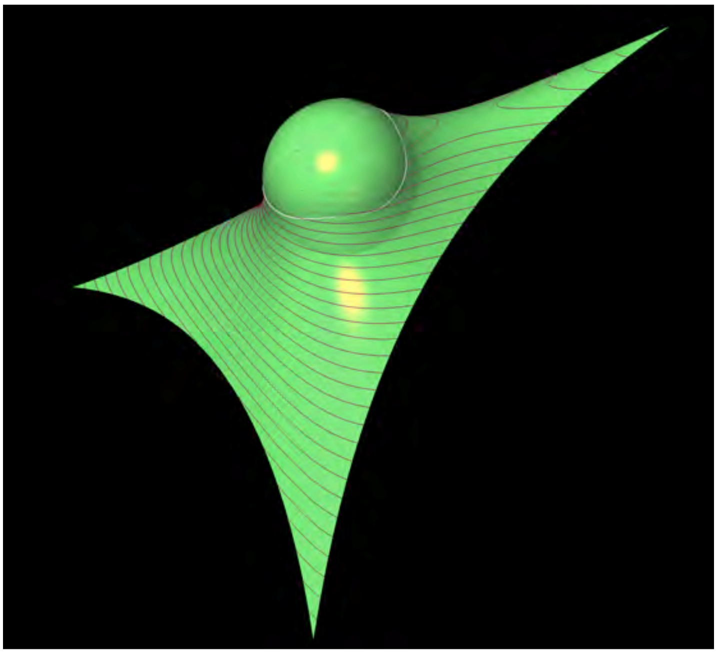

Figure 76: 3P-high, ø 80-03

9.4.3. 7P-2+2+3 high

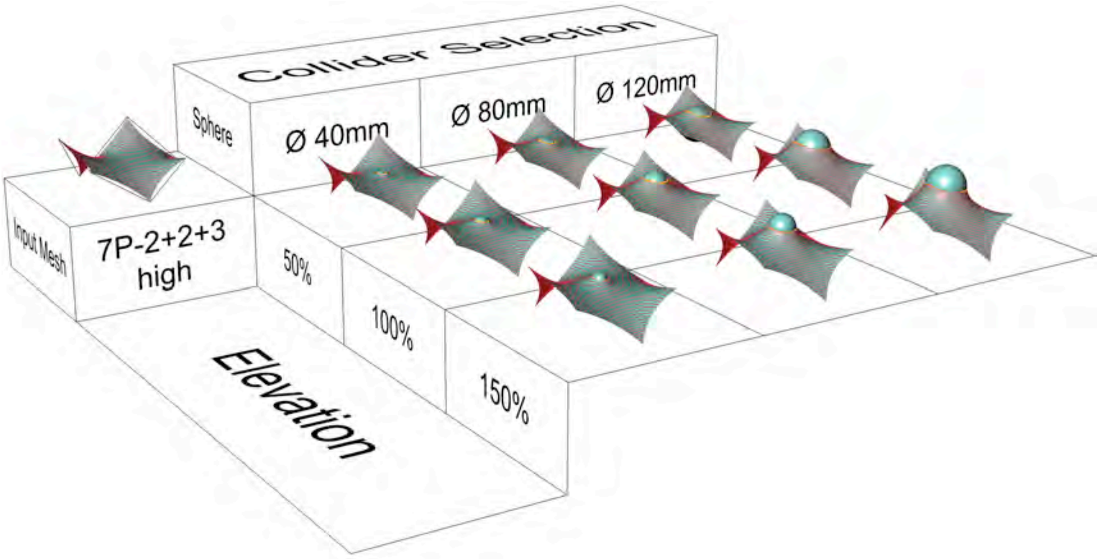

Figure 77: 7P-2+2+3 high Form evolution

The 7P-2+2+3 high models represent a particular case of interaction between boundary and highpoint. The membrane features an arrangement of alternating corner point heights. The central hump causes changes of shape, which are influenced by high corner points and low corner points alike. This allows for the observation of a sequential improvement of topography upon deformation. Two initial flat ponding areas are eliminated by subdivision into three cellular saddle surfaces. A general rule of deformation can be observed in this case. The form influencing effect of an internal highpoint is much greater when interacting with an adjacent high corner point than with any other boundary condition i.e. low point or edge line. The contact line remains only slightly twisted hence can be assumed as a ring. However it remains in a slightly tilted position.

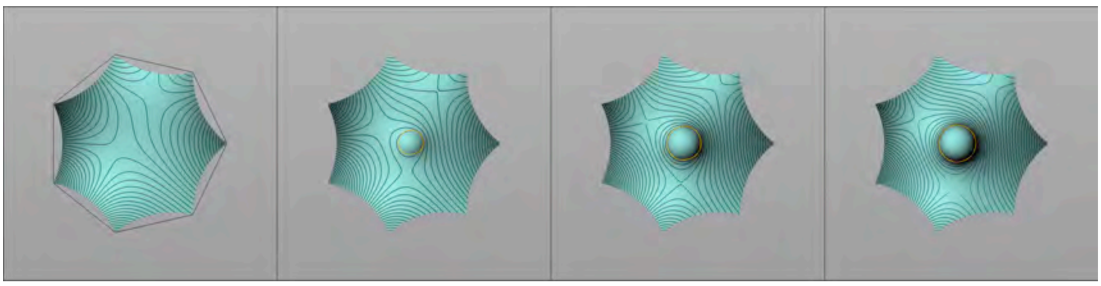

Figure 78: 7P-2+2+3 high 80-03

In figure 78 the contour lines of the experiment with 80 mm sphere are displayed in top view. Interestingly no substantial further shift of shape is performed between elevation 2 and 3, except the increase of height of the collider, which can be seen in perspective view.

9.5. Summary

The presented formfinding experiments evidence three leading conditions, which typically occur upon collision of a sphere onto a membrane of given initial shape. Each of them has variations, which result in a general rule of deformation.

1. Topography of initial surface:

- Flat membrane = Uniform conical shape
- Undulated or inclined membrane = Subdivision of mesh topology

2. Definition of boundary conditions:

- Low count of corner points = Pronounced influence on topography
- High count of corner points = Uniform conical shape

3. Neighbourhood between highpoint and boundary situation:

- Highpoint vs. low corner point = Downhill soft ridge
- Highpoint vs. high corner point = Uphill saddle shape
- Highpoint vs. low edge = Downhill slope
- Highpoint vs. high edge = Flat ponding area

All of the aforementioned phenomena are generally observed as simultaneous interaction of multiple factors. The hierarchy of form influencing factors corresponds to the order 1. to 3. above.

The leading indicator for the evaluation of topography is the geometry of the contact line. The curvature of the contact line reflects the sum of all form influencing factors i.e. boundary conditions, which are involved in the process of formfinding.

9.6. Exotic shapes

As announced above, a selection of non-trivial fromfinding results shall be presented as an outlook on more elaborate design ideas.

9.6.1. Ping-pong

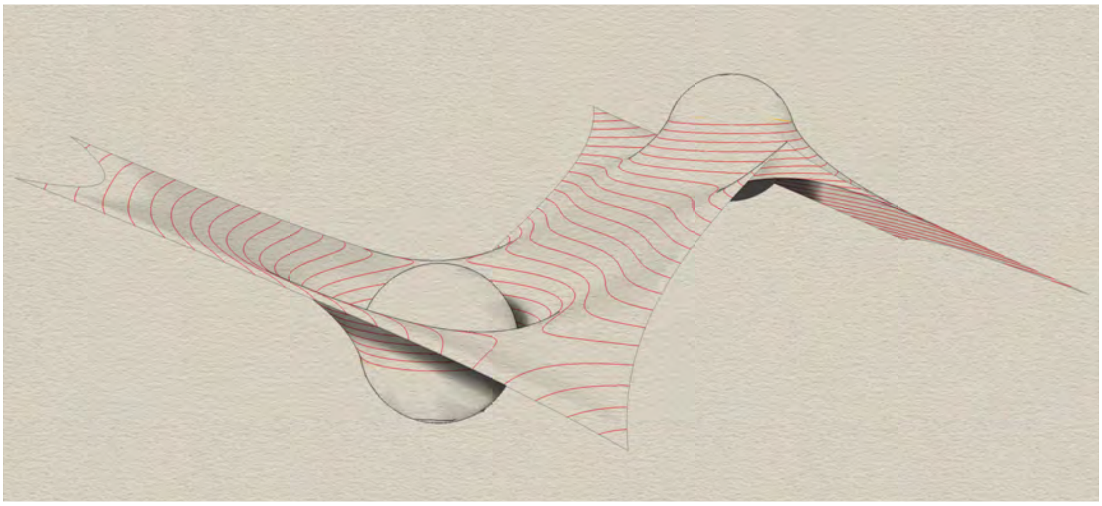

Figure 79: 2x5 with low point and high point

This beautiful tent is a simulation of a membrane with highpoints and low points. It is an inspiring proof for the versatility of application of humps as architectural and structural element.

9.6.2. Two discs

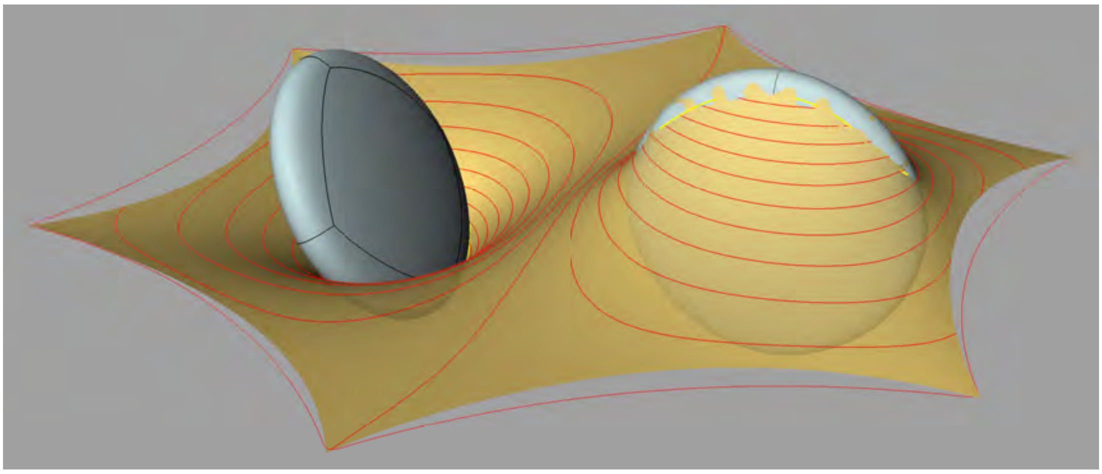

Figure 80: Two discs

A random arrangement of two rather unusual colliders is sculpting a flat membrane into a doubly curved landscape with interesting appearance.

9.6.3. Gempen

The Gempen is the local mountain in the backcountry of Basel, Switzerland. I grew up with this view. The form of this experiment resembles astoundingly the characteristic silhouette of the distinctive hill range.

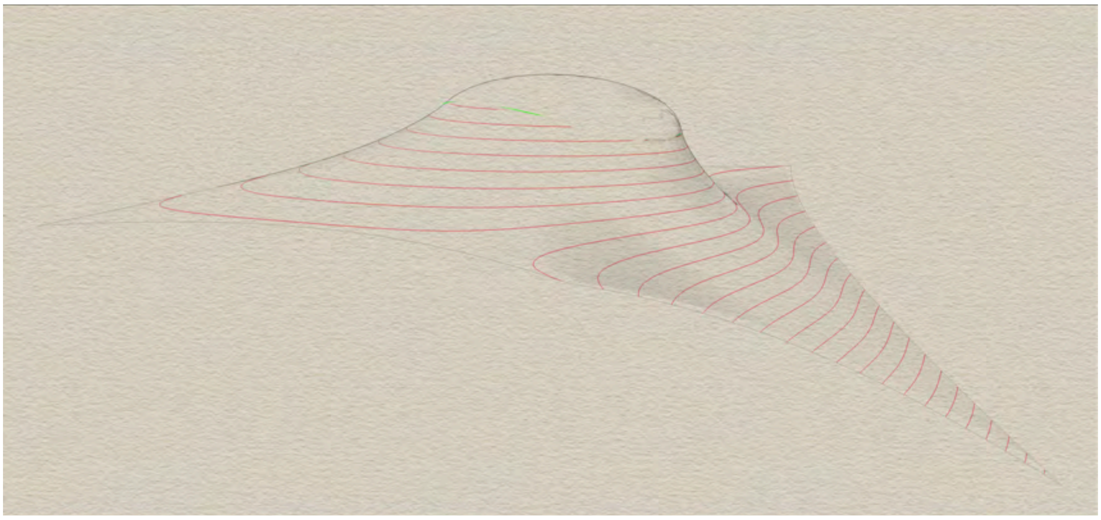

Figure 81: Gempen 1, 5P 4+1 low_oval 80-120-40 hor

The input curve here is 5P 4+1 low. The collider is an oval in horizontal position. The shape is full of aesthetic appeal due to good proportions and the diversity of curvature around the peak. As to technical feasibility the approach shows great promise as well.

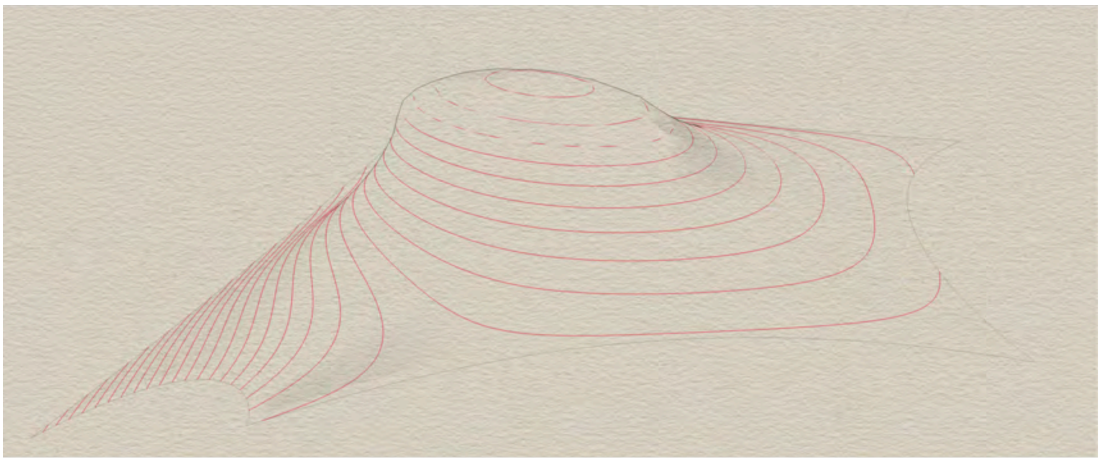

Figure 82: Gempen 2, 5P 4+1 low_oval 80-120-40 hor

9.6.4. Plateau

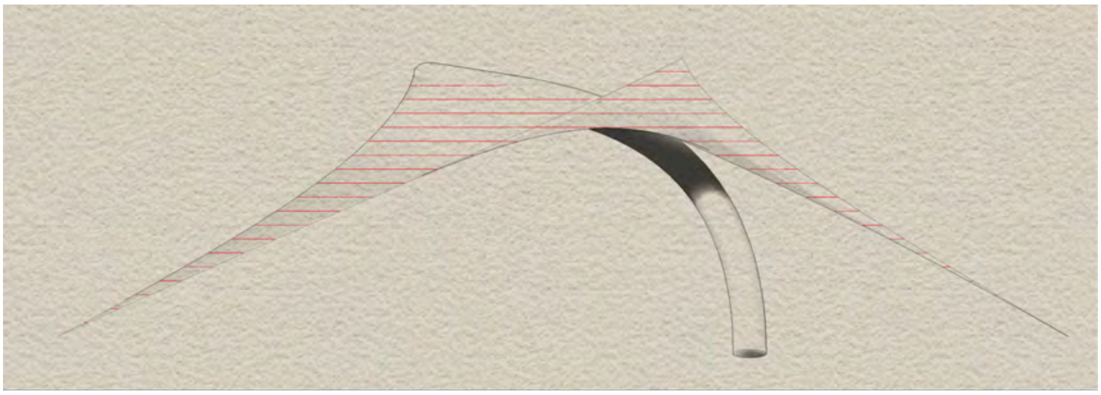

Figure 83: Plateau, 5P-low shackle spline-05, elevation

This experiment is trying to push the limits of eccentricity and at the same time to go into full cloth simulation with non-spherical i.e. free form colliders. Again a situation was chosen with strong initial curvature. The collider can be described as a shackle or a bracket. The collision causes a subdivision of the mesh and creates completely new surface areas, which are primarily controlled by the collider geometry yet are embraced by the initial boundary conditions.

Figure 84: Plateau, 5P-low shackel spline 05, perspective

10. Conclusion

To finalise this thesis a short summary of the conducted study shall be added and a discussion shall be initiated to act as a stimulus for architectural considerations and to give an outlook on further research.

10.1. Recapitulation

It has been documented that humped tents represent an ethnic genre in tent architecture, which goes back to nomadic life in antiquity. The basic way of highpoint creation perfectly matches the limited possibilities of archaic technology. The concept however has survived and was picked up by Frei Otto for his first contemporary membrane structures in the 1950s. Booming for a short period of time the humped tent soon fell into oblivion. The following evolution of membrane lightweight structures pursued a direction versus other challenges, which caused the humped tent to generally be left behind not only as a structural genus but in software development as well.

By means of case studies and by the study of literature it was shown that this kind of membrane structure consists of several subcategories and that their development is not finalised yet.

A large number of experiments on the basis of both physical and computational modelling strategies were successfully conducted. For both approaches, refinements were introduced or new methods were invented.

By visual assessment of the results from both analogue and numerical simulations the principal behaviour of humped membranes could be studied and were described. These observations constitute the groundwork for further research.

The introduction of newly developed methods, along with the outlook on unexplored shapes is disclosing the potential of future application.

10.2. Discussion ☺

These pages are meant to be an invitation to the interested participants in the field to pick the subject up. Two major threads are worth being discussed separately.

One is a debate on potential applications of humped surfaces in future tensile architecture.

The other is a road map of further research and consolidation on the subject of humped surfaces.

Architects & engineers

Typically architects and engineers lead a debate, which is motivated by design intentions and controlled by engineering constraints. Ultimately the debate is driven by economical enforcements.

Designing a textile roof or a tent often requires the introduction of a highpoint. Be it for reasons of quality of space, be for structural necessity or simply for the idea.

By reintroducing the humped surface unexpected possibilities of highpoint creation arise, which is a temptation for the designer. Given the multitude of possible supporting elements and arrangements architects and engineers alike will have to rethink the concept of struts. An assessment between feasibility and efficiency is necessary to evaluate esthetical and technical advantages yet prevent from adverse complications.

Further development

Based on the abovementioned the development will proceed from formfinding to analysis. In order to get a systematic understanding of stress distribution, the results of the numerical experiments must be charted. To complete the test series, additional experiments would be suitable comprising asymmetric i.e. exotic colliders and eccentric arrangements.

The software used for formfinding should be refined in a way as to provide more realistic stiffness settings. An upgrade of features to allow for the simulation of more complex structures is the natural evolution. As to engineering and production, the interface to other editors must be considered.

On a strictly empirical basis it would make sense to run through a number of full-scale prototypes. Material selection and patterning are the most crucial questions with both moderate and more pronounced forms i.e. natural and artificial humps.

List of Figures

List of Tables

List of Abbreviations

F.O.	Frei Otto
MLS.	Membrane Lightweight Structures
EL	Entwicklungsstätte für den Leichtbau
IL	Institut für leichte Flächentragwerke
IGA 63	International Horticultural Exhibition 1963
GH	Grashopper 3D®
Rhino	Rhinoceros 3D®
PSS	Particle-springs system
TMM	Toengi-mesh-machine.gh

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