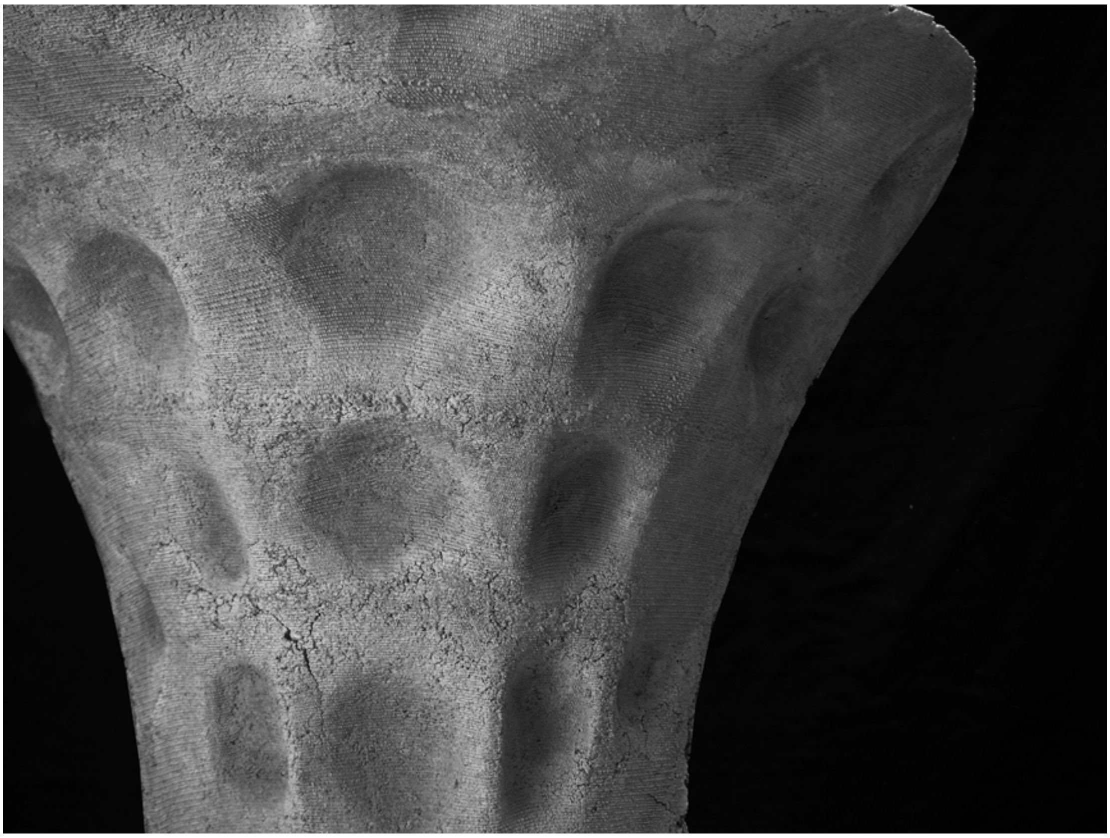
CHALMERS UNIVERSITY OF TECHNOLOGY



Shaping concrete

An investigation of knitted formwork for concrete casting

Master's thesis in Master's Program Structural Engineering and Building Technology

VERA SEHLSTEDT

Department of Architecture and Civil Engineering
Research Group for Architecture and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Master's Thesis ACEX30
Gothenburg, Sweden 2021

Master's thesis ACEX30

Shaping concrete

An investigation of knitted formwork for concrete casting

Master's Thesis in the Master's Programme Structural Engineering and Building Technology

VERA SEHLSTEDT

Department of Architecture and Civil Engineering
Research Group for Architecture and Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021

Forma betong

Utforskning av stickade gjutformar för betong

Master's Thesis in the Master's Programme Structural Engineering and Building Technology
VERA SEHLSTEDT

Examensarbete ACEX30
Instutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2021

Department of Architecture and Civil Engineering
Research Group Architecture and Engineering
Chalmers University of Technology
SE-41296 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Model scale 1:5 of concrete shell

Department of Architecture and Civil Engineering
Göteborg, Sweden, 2021

Shaping concrete
An investigation of knitted formwork for concrete casting
Master's thesis in the Master's Programme Structural Engineering and Building Technology
VERA SEHLSTEDT

Department of Architecture and Civil Engineering
Research group for Architecture and Engineering
Chalmers University of Technology

ABSTRACT

Double-curved geometries have never been easier to design with the advancements in 3d software. However, realizing these structures are often complicated, time-consuming, and wasteful. The formwork for casting concrete structures represents more than half of the total cost for complex geometries making it unfeasible in most cases. Not only does this limit the architectural expression but also the engineering possibilities. Admired structures, such as the ones built by acclaimed engineers like Felix Candela and Pier Luigi Nervi, rely on curved geometry to carry the load efficiently.

In this thesis, knitted formwork is examined as an alternative production method for double-curved geometries. The production method is studied to optimize the production phase to increase the feasibility of such complex structures. In addition, the method is also studied to produce efficient structures to reduce material usage in the structural system.

The exploration of knitted formwork is done in a design study where models of varying scales are produced. To complement the physical models, computational simulations are performed to support the design process by generating knitting patterns, form-finding and analysis of the shell structure. The final design is a result of an iterative design process where the fabrication method, as well as the structural system, is expressed. Only when these are in symbiosis can the design be a representation of efficiency.

Keywords:

Knitted formwork
Form finding
Shell structures
Concrete casting
Digital fabrication

PREFACE

The thesis stems from the appreciation of and admiration for great tectonic architecture. The pioneers within structural engineering were renaissance men, combining their knowledge in engineering, building and architecture. We still have much to learn from them as the building sector is faced with the environmental challenges of our time. In bringing back holistic thinking, linking the production to the finished structural system, can a more true efficiency be reached.

ACKNOWLEDGEMENTS

Firstly I would like to acknowledge the contribution of August Sjölin and thank him for the collaboration during the thesis work. I would also like to thank August's supervisor, Jens Olsson, for his insight and support during the thesis work.

I would also like to show my gratitude to my examiner Dr. Mats Ander and supervisor Prof. Karl-Gunnar Olsson. Their joint enthusiasm and guidance have been nothing short of priceless. I would also like to thank Rastislav Bartek for his support.

Last but not least a big thanks to my opponents Maria Roll Bruzell and Alexander Angrén for their conversations during this work.

WORDLIST

Course direction - *The direction of the width of a knit, that is decided by the number of needles/loops*
Eigenmode pattern - *Color gradient of deformation under applied eigenfrequency*
Falsework - *Temporary scaffolding etc that supports the form.*
Formwork - *Elements that come in direct contact with the wet concrete giving its form.*
Gaussian curvature - *Product of the principal curvatures in a point of a surface*
Minimal surface - *A surface of the minimal area within a given boundary, mathematically represented having zero mean curvature*
Pareto front - *The pool of optimal solutions for several parameters*
PSS- *Particle spring system*
Wale direction - *The direction along the length of the knit that is decided by the numbers of rows that are knitted*
Short-rowing - *When a knitted row stops short leaving loops from being knitted that row*

CONTENT

1. INTRODUCTION 1

1.1 Aim 1

1.2 Method 1

2. CONTEXT 3

2.1 Efficient concrete structures 3

2.1.1 Concrete structures 3

2.1.1.1 Non-prismatic structural members 4

2.1.1.2 Concrete shells 4

2.1.2 Fabric structures 6

2.2 Production methods 6

2.2.1 Casting concrete 7

2.2.1.1 Cast-in-place 7

2.2.1.2 Pre-cast 8

2.2.1.3 Sliding formwork 9

2.2.1.4 Flexible formwork 9

2.2.2 Membrane patterning 11

2.2.3 Knitting production 12

2.3 Theoretical principles 14

2.3.1 Shell analysis 14

2.3.2 Computational simulation of fabric 14

2.3.3 Form-finding 15

2.3.4 Particle spring system 16

2.3.5 Eigenmode parametrisation 17

3. LIMITATIONS 18

4. DESIGN STUDY 19

4.1 Site and constraints for design proposal 19

4.2 Methodology 20

4.3 Material study 21
4.3.1 Knitting samples 21
4.3.2 Casted knitting samples 23
4.3.3 Computational model 27
4.3.4 Stretch test 28
4.3.5 Reflections from material study 29
4.4 Model study 30
4.4.1 Structural element 30
4.4.2 Structural concept 32
4.4.3 Shaping knitting pattern 32
4.4.4 Model of umbrella structure 35
4.4.5 Digital model compared with physical model 37
4.4.6 Eigenmode pattern redistribution of mass 38
4.4.7 Model with inflated pockets 39
4.4.8 Reflection from model study 41
4.5 Final design 42
4.5.1 Concept of structural system 42
4.5.2 Fabrication of element 44
4.5.3 Erection sequence of umbrella 44
4.5.4 Model study of umbrella fabrication 46
4.5.5 Design flow 51
4.5.6 FE-analysis 52
4.5.7 Comparison to flat slab 56
4.5.8 Reflection from final design 57

5. DISCUSSION 59

6. CONCLUSION AND FUTURE WORK 64

BIBLIOGRAPHY 65

1. Introduction

"…the most fertile, ductile and complete construction method that mankind has yet found", is just one of many quotes about concrete from Pier Nervi's book Aesthetics and Technology in Building (1965). According to Nervi, this enormous potential of concrete is due to two properties that no other material possesses, (1) its semifluid initial state during casting and (2) the monolithic quality of the final product.

Today concrete is the material that is used the most of all materials in the construction industry. It is also known that this industry is responsible for approximately 40% of the global carbon equivalent emissions as well as produces 40% of the global waste (Block, 2020). Knowing both the scale of use and the environmental impact of the industry, it becomes crucial to use the material efficiently. When reducing material, the structure relies on geometrical stiffness rather than the sheer volume of mass. It is instead only placed where needed, following the logic of the internal forces. This however imposes challenges in productions as the complexity of the shape is increased. (Popescu, 2019)

1.1. Aim

The main focus of this master thesis is to examine knitted formwork for casting concrete structures. Exploring if knitted formwork can be an efficient solution to producing complex geometries that might otherwise be difficult to achieve. The efficiency of a concrete element that is the result from casting using knitted formwork will also be studied. This is done to evaluate if the production method of knitted formwork not only decreasing cost, labour and waste in production but also reduce the volume of concrete in the structural element.

1.2. Method

The thesis is done in two parts, a literary study, and a design study. The literary study is done to research the field of efficient structures in concrete and membrane structurers. In relation to this is also the production methods for concrete structures as well as membrane structures studied. In the literary study is also the theoretical principles applied in the design study researched. This work is presented in the Chapter 2, the contextualization and is a starting point for the design study.

The design study is where the knitted formwork is examined. This is done in an iterative matter, starting small and building an understanding for the knit's structure at a basic level. With that knowledge can complexity be added and go up in scale. The exploration is mainly through physical models. The three stages of the design study are: *Material study*, *Model study* and *Final design*. In the first stage, Material study, is the focus to explore the possibilities of the knitted fabric in relation to concrete casting. This is done by generating many samples in an aimless manner and then postprocessing the result to evaluate which methods have qualities that can be used in the design proposal. In the Model study is the design process done in a more controlled manner where a sought-after result is strived for. However, the process is still in a trial-and-error stage where the method for finding the wished result is iterated. In the last stage, Final design, is the resulting design evaluated. The aim is to use the design study as a tool to demonstrate knitted formwork and a resulting structural system in a project setting. In Chapter 4.2 is a thorough methodology for the design study presented.

The design study is done in parallel with architect student August Sjölin. His research is regarding contemporary ornaments and explores if ornaments can be based on structural performance and/or the fabrication method. For further reading please refer to Sjölin's thesis "Ornament and Structure – a reconnection to ornament through knitted formwork". The collaboration is mainly connected to model making and illustrations.

2. Context

The contextualization of the research is done in this chapter by picking key historic or contemporary example that relates to the research presented in this paper. Examples of efficient structures and production methods are presented both as a source of learning and inspiration. The context will also serve as a basis for the discussion, where the research presented in this thesis can be weighted against.

2.1. Efficient structures

The structural efficiency for a single element can be measured as the actual stress over maximum allowed stress. As for a structural system the mass of the structure is related to the load carried. In the following chapters, structures that can in some sense be described as efficient will be presented that are relevant for the thesis.

2.1.1. Concrete structures

Today the overwhelming majority of concrete is used to create straight beams and prismatic columns. Elements that express no desire or consideration for the internal forces. As concrete is a large greenhouse gas contributor, 4-8% of the global CO_2 emissions, (Watts, 2019) which also implies that the more efficient structural systems for concrete can have a large impact on the industry's overall environmental footprint. Where material used is used only where needed in a reserved and deliberate manner.

Figure 2.1 Pier Luigi Nervi, Floor system in tobacco factory, Bologna, 1949

2.1.1.1. Non-prismatic structural members

A structural member seldom has the same stresses throughout the whole length of it. Diagrams for bending moment, shear and normal stress are common design tools for engineers. It shows how the forces acting on the member vary along the length. Instead of only extract peak values and design thereafter, the diagrams can inform the design for a non-prismatic element.

In Nervi's Tobacco factory the internal forces shape the geometry. Ribs of reinforcements create a grid pattern, where the ribs' cross-sections vary along the span. The fixed ends of the ribs where the moment peaks, are also where more material is added. The same logic is used for the beams creating a harmonious architectural expression ruled by "logical shaping". (Nervi, 1965)

In Figure 2.2 a beam designed by Mark West can be seen. Here the moment diagram is used as a starting point when designing the beam. The rather organic shape reflects the peak moments over the supports and middle of the span.

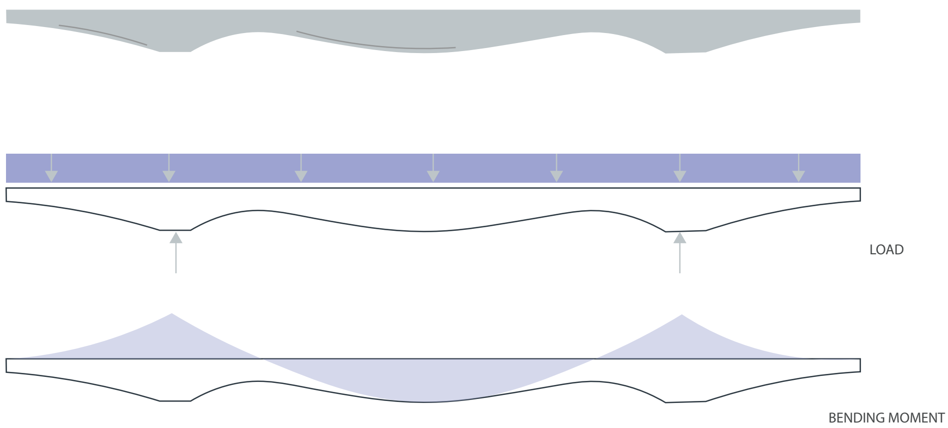


Figure 2.2 Mark West's non-prismatic beam shaped by the moment diagram from uniform load

2.1.1.2. Concrete shells

Shell structures are mostly classified through their geometry consisting of a curved surface that is thin in the perpendicular direction. These structures work primarily with in-plane membrane stresses since the thin section has limited bending capacity. To eliminate bending moments the geometry of the shell needs to be carefully designed. (Williams, 2014)

Shell structures had their prime year 1920-1960 (Veenendaal, 2017). Félix Candela is credited to play a large role in the development and implementation of shell structures. Candela was very productive during his career designing a large number of shells. One of the more recognized works by Candela and his self-proclaimed favorites is the Restaurante Los Manantiales in Xochimilco from 1958. The shell structure is constructed out of an eight-sided groin vault where four hyperbolic paraboloids intersect. The thinness of the structure is striking, only 4cm thick.

The light structure could be achieved due to Candela's exemplary intuition and experience with concrete shells. Normally, would the dead load of the structure caused bending in the groins. As the groins bows outward this would push at the saddles forcing the edge to balloon out. This deformation would have caused cracks to propagate at the edge going inwards. To prevent cracking the edge could be stiffened with an edge beam. However, Candela did not consider the shell structure pure if the thinness could not be expressed through the sharp edge.

Instead of addressing the edge, Candela addressed the groin. The shell thickness increases in the groins, creating V-shaped beams. This eliminates the problematic deformation and instead, tension forces occur at the edge. Rather pulling the edge backward and eliminating the need to stiffen the edge. (Burger, Billington, 2006)

Figure 2.3 Félix Candela, Los Manantiales Restaurant, Xochimilco, Mexico City, 1958

2.1.2 Fabric structures

Fabric or membrane structures have long been used in architecture. It is used in the smallest scale of architecture as a tent, ranging to some of the largest structures, arenas. Membrane structures are extremely light but through curvature and pretension can carry significant loads (Bechthold, 2008). Characteristic for tensile structures is their anticlastic shape to ensure that the load is carried in tension.

Under tensile load, the fabric will strive for a minimal shape and if it is not already adopted the fabric will wrinkle. A minimal surface is the shape of the surface that has the smallest area within the boundary. This can be described mathematically by a surface where the mean curvature is zero at all points. (Olsson, 2020)

Structural engineer Frei Otto was active at the Institute of Light Weight structures in Stuttgart. The institute and Otto himself are credited with many developments within the field of minimal surfaces and tensile structures. (Olsson, 2020) The roof for the Olympic Stadium in Munich for the Summer Olympics in 1972 is one of the most recognized works by Otto.

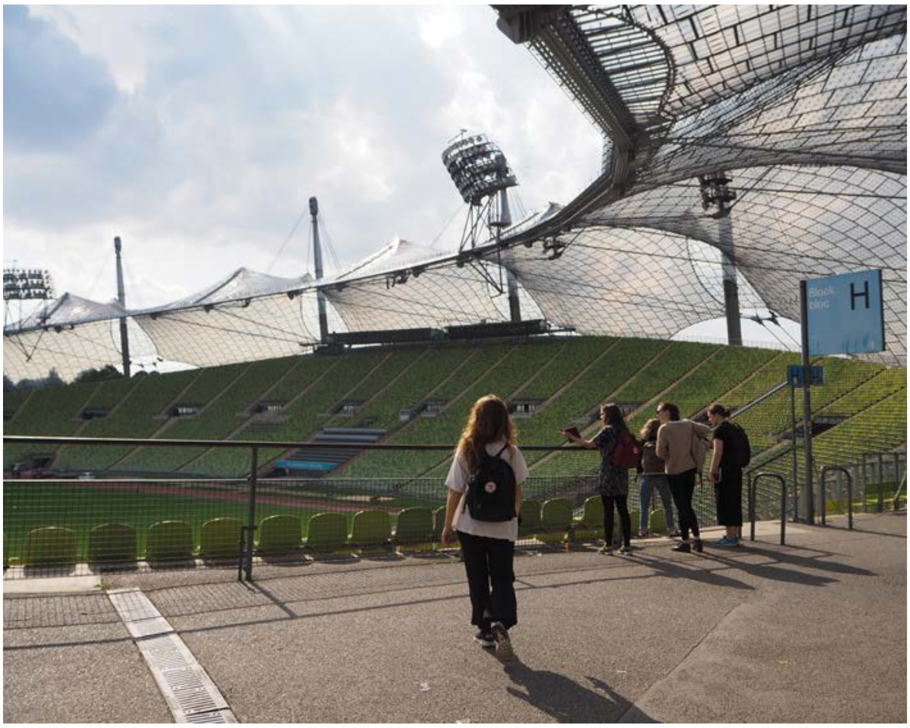


Figure 2.4 Frei Otto, Munich Olympic stadium membrane roof structure, 1972

2.2. Production methods

It becomes evident by examining examples of efficient structures that a complexity of geometry is added. This complexity will affect the production with parameters such as cost, time and waste. Limiting the reach of these types of geometries to iconic buildings where the budget allows for it. (Popescu, 2019)

2.2.1. Casting concrete

The possible geometries that can be achieved when producing concrete are limited by the material used to produce the formwork, as it is a reflection of it (Olsson, 2020). Many of the pioneers in shell structures also had a long experience in not only design but also construction. This was crucial since the shell's thinness and curvature made the construction difficult. (Billington, 1990)

The formwork also stands for a significant part of the total cost of a structure, it is estimated to be accountable for approximately 50% of the total coast. When the element has a highly complex geometry the formwork cost can represent more than 70% of the total cost. (Popescu, 2019)

2.2.1.1. Cast-in-place

Shell structures are most commonly cast-in-place structures. The framework is usually made from timber by skilled carpenters. For complex double-curved geometry, the timber must be bent, or CNC milled. This process can be time-consuming and wasteful. The material for the formwork can seldom be reused and ends up as waste.

Felix Candela factored the building process into the design. Candela's hyperbolic paraboloids shaped shells could be constructed by linear elements since the surface is a ruled surface. This significantly reduced the cost and facilitated the construction process.

Figure 2.5 Félix Candela, Los Manantiales Restaurant, Xochimilco, Mexico City, 1958

2.2.1.2. Pre-cast

Casting off-site and bringing complete elements onto site can be an option to reduce some of the need for extensive scaffolding (Billington, 1990). The same mold can also be used to produce several elements and the level of accuracy is higher. However, there are some limitations to pre-casting elements. The size of the elements is restricted to transport but also the on-site connections are more demanding. (Olsson, 2020)

The dome structure in Nervis's Palazzo dello Sport consists of a combination of pre-cast and casting on site. The dome structure is approximately 100 meters in diameter, with pre-cast ferrocement units originating from the center and radiating outwards. Ferrocement is constructed by encasing a thin mesh of rebar in mortar. The rows of V-shaped units vary in depth from 0.3m to 1.2m at the edge. On top of the V-shapes are precast slabs placed. In-situ reinforced concrete is cast in the valleys and crests making the outer surface homogenous. The dome structure was completed in only 2.5 months. (Campbell, 1959)

The dome is not only an example of fast and efficient construction but also an efficient structural system. In a half-sphere, the hoop stresses in the top are in compression and change to tension in the bottom part. As the dome of Palazzo dello Sport is cut at the level where the hoop stresses changes sign the result is a dome structure in pure compression under gravity load.

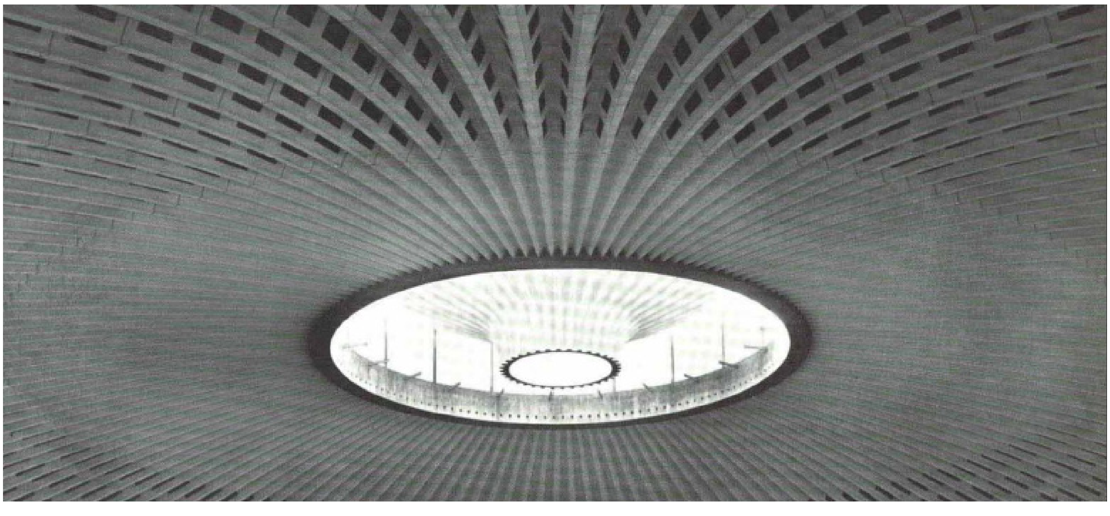


Figure 2.6 Roof structure of Palazzo dello Sport, Nervi, 1959

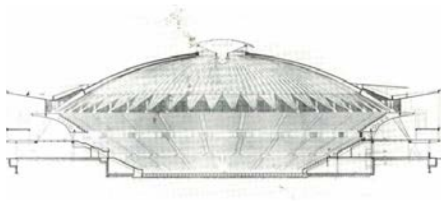


Figure 2.7 Section drawing of V-shaped units and the entire buildings

2.2.1.3. Sliding formwork

To reduce the cost of the formwork can a partial mold be used that can slide. A sliding formwork was used for the Tobacco factory to reduce the cost of the intricate geometry. The slab was cast in segments as seen in Figure 2.8. When the slab was self-supporting the mold was lowered and slid on the tracks to the next position.

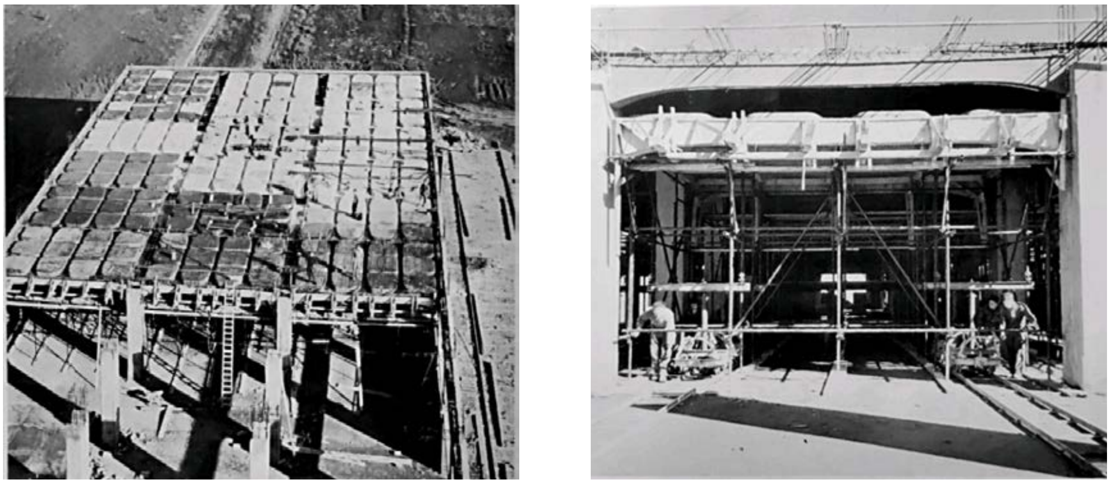


Figure 2.8 Nervi, Sliding formwork for Tobacco factory, 1949

The geometry of the building limits the use of sliding formwork. Linear buildings with for instance flat slabs or barrel roofs are well suited. As well as domes where a pie-shaped formwork slides in a circle.

Another drawback is that the structure must be self-supporting when incomplete. For instance, a dome structure would have to be self-supporting without any hoop stresses. (Billington, 1990)

2.2.1.4. Flexible formwork

Within the field of flexible formwork, there are different approaches. Some of the approaches are using a woven fabric, cable net and knitted formwork.

The beam seen in Figure 2.2 is formed by fabric formwork. But also larger elements such as the three columns in Omer Arbel’s project 75.9. The elements are formed by pouring concrete into a fabric that was restrained by plywood ribs. The concrete was poured at a slow pace to let it cure simultaneously to limit the hydrostatic pressure on the base. The fabric releases air bubbles from the concrete through micro-perforations. (Arbel, 2018) If the fabric is water-permeable excess water in the concrete can escape that’s not chemically bound. This can increase the quality of the concrete as too high water content will reduce the concrete strength. (West, 2016)

A significant amount of research at ETH Zurich has been done in the area of flexible formwork. A hyperbolic paraboloid shell was constructed by casting concrete on a

Figure 2.9 Omer Arbel, 75.9 construction process, Surrey, Canada, 2018

pre-tensioned grid of cables. The shape is well known from buildings by Candela among others. However, the shell geometry was not limited to a ruled surface which was used when constructing the formwork from straight timber members. The freedom enabled the shell to be optimized and have increased stiffness. (Block, Veenendaal, 2014)

ETH Zurich along with ZHCODE constructed a 5 tone sculpture using knitted fabric formwork as guide work. The knitted formwork had an integrated cable network and air pockets and the total weight of the formwork was 55kg. (Popescu, 2019)

Figure 2.10 ETH & ZHCODE, KnitCandela, Mexico, 2018 (photo credits: Angelica Ibarra).)

2.2.2. Membrane patterning

Where woven fabrics or other foils are used for tensile membrane structure, a cutting pattern is necessary to cut, sew and assemble the structure. The patterning can be quite difficult to be designed since it's based on the final tensioned shape and therefore must be offset with regards to strain and Poisson's ratio. The final geometry which is often a double-curved geometry also needs to be discretized into smaller developable surfaces that can be cut from the fabric.

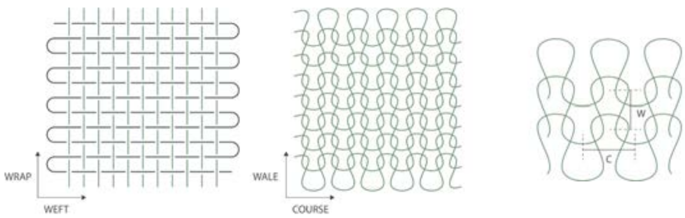


Figure 2.11 Woven and knitted fabric with zoom on knitted fabric

When using knitting the fabric can be manipulated by the different operations as seen in Figure 2.16. The operation to increase, decrease and slip can redirect material and create 3D shapes. This results in a significant part of the manual labor can be eliminated when knitted fabrics are used for a double-curved surface.

At ETH Zurich an open-source tool for generating knitting patterns has been developed. A mesh based on the loop height and width is generated on the desired surface. Each loop is representing a square, with each triangle representing an operation, either increase, decrease or slip. When loops are slipped it is called short rowing as that row stops short. Loops from the previous row will stretch over to the next knitted row, adding volume to where the loops are not slipped.

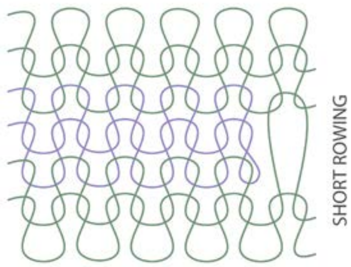


Figure 2.12 Short-rowing description

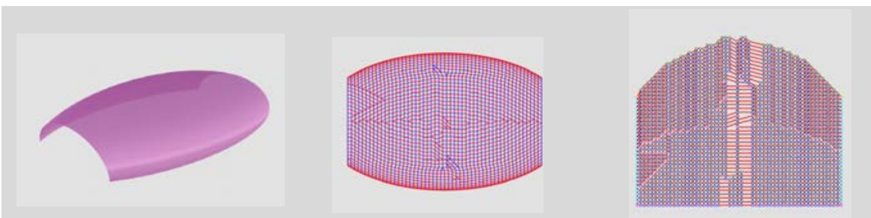


Figure 2.13 Knitting patterning generated using Rhino/Grasshopper plug-in Cockatoo

2.2.3. Knitting production

Knitting is believed to have been around since the 5th century as a method to produce fabrics. It has a rich history and traditions with different techniques. As in most industries, significant developments have been made to automate to process for mass production. However, the different techniques of how to interlock the loops of yarn are still the same but now produced with machines rather than by hand.

A flatbed knitting machine consists of the needle bed and the carriage. The carriage travels back and forth over the needle bed with the yarn. When the carriage moves over a needle it causes this needle to be pushed out and in, this movement enables the needle to catch the yarn and pull the previous loop over the yarn creating a new one.

Usually the there is two needle bed facing each other. The upper array of needles is the main bed and the lower array the ribber bed. The most simple knit, the single jersey is knitted using only the main bed. The more elastic knit, the double jersey is knitted one every other needle on the main and ribber bed.

The knitted running shoe is a good example of CNC knitting. The shoe features change in geometry, colors and yarns and integrated channels/holes for the lace. All of this is done in on simultaneous knit in one go. A CNC knitting machine is fed with a pattern made up of pixels with different colors. Each pixel controls one needle and the color describes the movement of the needle.

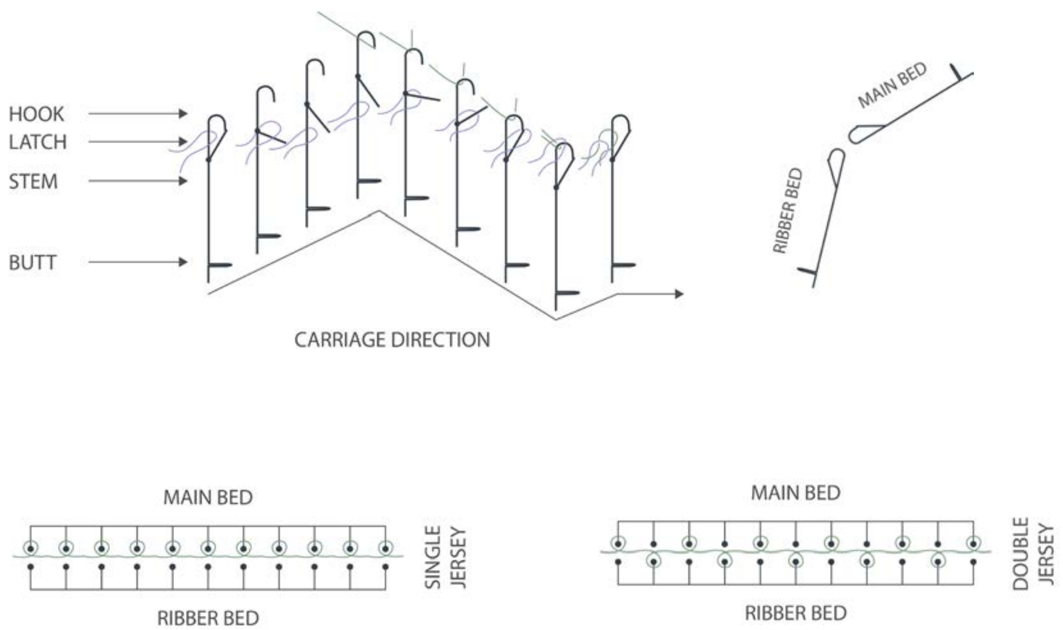


Figure 2.14 Single needle forming a new loop and set-up with two needle beds

The complexity of the operations depends on the machine. The SK840 with a ribber SRP60N that Chalmers University has can be programmed to knit or not knit (slip) using a color chart and pick between yarns. However, transfers have to be done by hand. On an industrial-grade machine all of these operations can be programmed. Once the pixel map of the pattern is generated, the machine will knit without any human interaction needed.

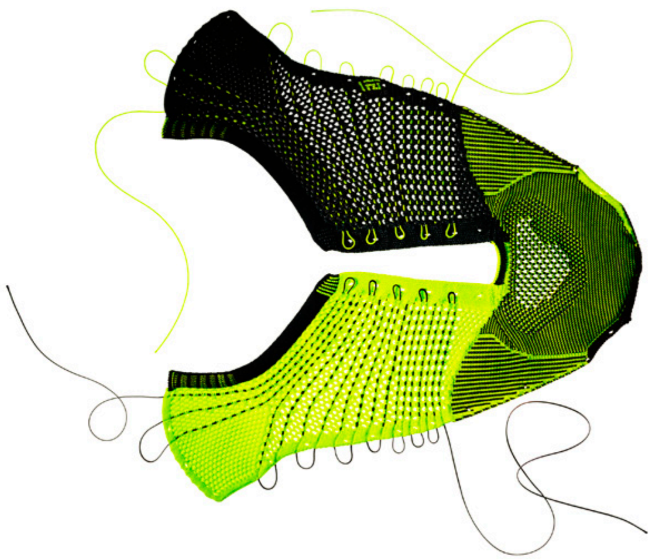


Figure 2.15 Nike knitfly, Knitted shoe upper, 2012

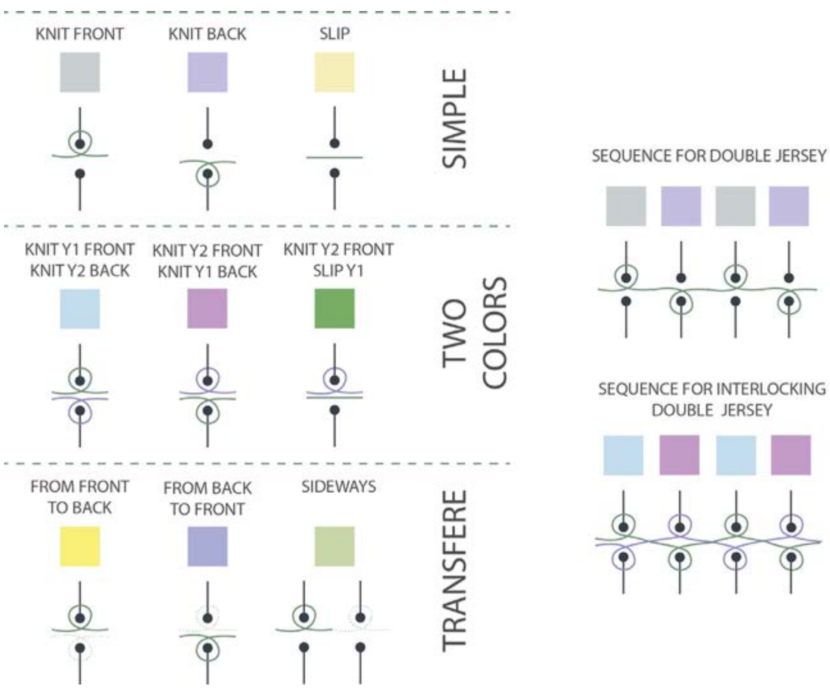


Figure 2.16 Examples of pixel and pixel sequences for pattern making

2.3. Theoretical principles

In the following chapters, theory applied in the design study will be presented. The theory will be used both as a comparison to physical models and as a design tool.

2.3.1. Shell analysis

Shell structures are mostly classified through their geometry consisting of a curved surface that is thin in the normal direction. For a shell, all the modes of other structures, such as beams, struts, cables, plates are available with the addition of 'shell action'. In-plane membrane stresses are a central part of shell theory. There are three unknown stresses, the normal stress in x- and y-direction and shear stress perpendicular to each of the normal stresses, which through moment equilibrium can be determined to be equal. From the plane stresses there are two equations of equilibrium.

For the membrane theory of shells, the same in-plane stresses are used. However, with the addition of the equilibrium equation. The equation is in the perpendicular direction of the tangent of the shell surface. The force is balanced with the membrane stresses multiplied by the curvature. Since the curvature has the unit m^{-1}, the load would have unit kNm^{-2}, and the membrane stresses kNm^{-1}.

The curvature of a shell is often described by using Gaussian curvature. The Gaussian curvature is the product of the two principal curves of the surface. A synclastic surface has positive Gaussian curvature, an example of this is a dome. The anticlastic surface has negative Gaussian curvature, such as a saddle. For a surface with zero Gaussian curvature, the surface is also developable and could be laid flat, for example, a cylinder. (Williams, 2014)

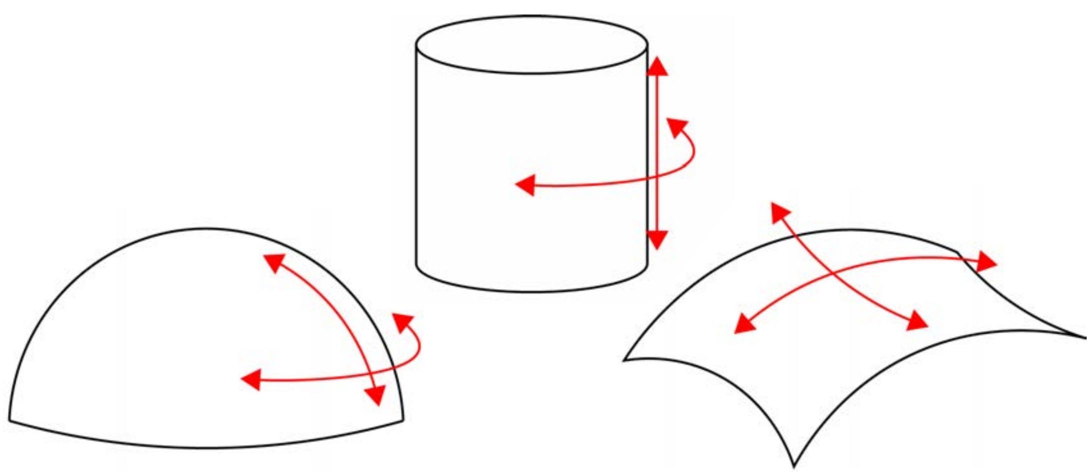


Figure 2.17 Dome (positive Gaussian curvature), cylinder (zero Gaussian curvature), saddle (negative Gaussian curvature).

Due to the thinness of the shells, the bending stiffness is limited. Therefore it is desirable to have a funicular shell that carries the load in membrane action with no bending moment. Concrete's mechanical properties allow for much greater compression forces than tension forces. Therefore concrete shells are usually designed to be in primary compression. To limit the need for reinforcement is beneficial as this can be very complex for doubly curved surfaces as shells.

One of the most common failure modes for concrete is local buckling. Since the shell is often in compression with a thin cross-section, local instability is often of great concern. (Williams, 2014) One option that is often seen in for instance Nervi's structures is increasing the stiffness by introducing ribs. The ribs stiffen the surface without adding as much material as if the entire shell thickness is increased.

2.3.2. Computational simulation of fabric

Simulation of fabric can be a complicated matter. Simulation on a larger scale, like the one of architecture, the textile is usually simplified to a continuous surface or course mesh containing the mechanical properties. The material properties are usually orthotropic, for instance, the stiffness in each directions. (Hörteborn, 2020)

When simulating a knitted fabric, it is even more complicated than for a woven fabric. For a woven fabric several threads are acting parallel to each other as for the knitted fabric a single thread is looped together. The behavior of interlocking loops and the friction of sliding the loops are difficult to capture.

By translating the knit into a hexagonal grid containing "interlocking" elements that can slide along the neighboring elements have Cirio et al (2016) been able to digitally simulate the behavior of the knit on a loop level. This is done to represent knitted fabric for computer graphics.

2.3.3. Form-finding

The field of form-finding is especially important for membrane and shell structures. For a tensile membrane, the form-finding process is crucial to make certain that the membrane will contain its shape and eliminate wrinkling of the surface.

For shell structures, the form-finding is to eliminate bending moments to ensure that the shell works primarily with in-plane stresses. Concrete as known is weak in tension but very strong in compression. Therefore, the goal of form-finding a concrete shell is often to have a structure in primary compression. The hanging model analogy is often used for this purpose both in physical models and computational models. The most primitive version of the analogy is when inverting the shape of a hanging chain the structure will go from pure tension to pure compression. (Bechthold, 2008)

Antoni Gaudí modeled Sagrada de Familia using string and weights. The weight was the self-weight of the structure and the strings adopted their shape according to the weights. Heinz Isler used sheets as a tool for form-finding his shell structure. (Chilton, 2010) The sheets were hung, and the shape inverted going from a sheet in tension to a shell in compression as seen in Figure 2.18.

Figure 2.18 Heinz Isler, Physical form-finding by hanging fabrics and construction of concrete shell designed, Norwich Sports Park, Norwich England, 1991

2.3.4. Particle spring system

The objective of the particle spring system is to find a shape in statical equilibrium. A system is discretized into a network of springs and particles. The springs have an associated length and stiffness, and the particles have a mass and load. The system has converged when the sum of the forces in the system equalizes. For instance, can the particles can be loaded with gravitational pull causing the springs to elongate. This elongation of the spring generates a force in the spring and the system converges when the force in the spring eliminates the downward force from the gravitational pull. The motion of the particles is governed by Newton's second law and the force of the spring is governed by Hook's law.

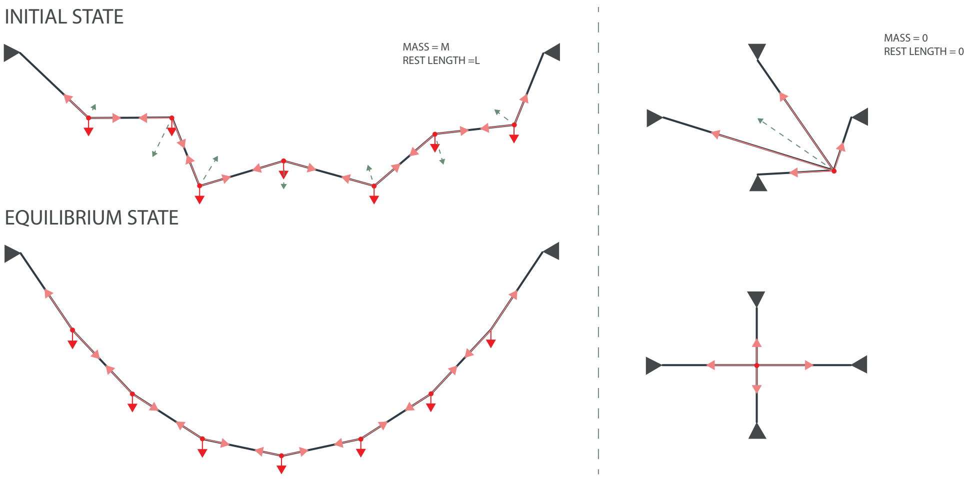


Figure 2.19 Hanging model simulation and stretching of fabric using PSS

When applying the method of PS systems there are a few parameters that control the outcome. Boundary conditions are important and will affect the result greatly. This determines which nodes are free to move and which are fixed in space. The parameter of the rest length and the loading of every node determines the “goal” of the simulation. This model can be used to simulate hanging models such as Gaudi and Isler used, but also stretching of fabric as seen in Figure 2.19.

For the simulation of knitted fabric, a small rest length is set. This will simulate the stretching of the fabric between the prescribed boundary curves. The load in the particles is not relevant in this case since the tension of stretching the fabric will be much greater than the load caused by the weight of the fabric. (Block, 2016)

2.3.5. Eigenmode parametrisation

When shells are designed as pure compression shells it is usually for the dominating load case, for instance, the self-weight. The structure also has to resist additional loading, non-symmetrical loads and geometrical imperfections. The full spectrum of load cases will most likely impose some bending moments in the structure. In addition, the shell has to be designed for instability such as local buckling. The shell can be dimensioned so that it can handle such load by having a thicker shell or stiffeners can be used. Much like the roof of the sports arena by Nervi where the dome interacts with a diagrid of beam/stiffeners.

When designing a shell with ribs the placement of the stiffeners needs to be superimposed on the shell geometry. This can be difficult as the surface geometry’s complexity can make it difficult to orient. One way to parametrize the surface to find the placement of ribs or openings was proposed by Panagiotis Michalatos and Sawako Kaijima (2014) is to use the vibration eigenmodes. The patterns themselves are not per default the optimal solution but need to be post-processed to find which pattern performs the best.

The advantages of using the eigenmode pattern are that the result of the optimization process will be a logical pattern as opposed to a random-looking and scattered result. The result is also visually strong and could contribute to the architectural expression.

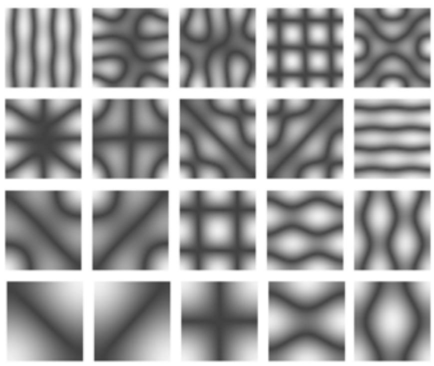


Figure 2.20 First 20 vibration patterns for square plate

3. Limitations

The thesis will compare casting with knitted formwork to other production methods regarding aspects such as waste, labour, time and environmental impact. However, a full carbon footprint in a life cycle analysis is not in the scope. The comparison will instead be based on literary study and empirical results from the design study.

As the thesis aims to explore knitted formwork in a project setting is a site in Gothenburg is chosen. The site will serve as a reference for dimensions etc. The design study will result in one conceptual design for a key element in the building but not resolve the structural system in its entirety. Foundation and ground conditions will not be considered.

The design study is also done in collaboration together with August Sjölin, a student doing his Master's Thesis in architecture at Chalmers University. This imposes other demands from an architectural point, for example spatial, acoustical and artistic that will make the project more complete in its entirety. The collaboration is not only a source of limitations but first and foremost a great source of inspiration, guidance and help to achieve a well-rounded project.

For examination of the knitted fabric's behavior is an SK840 knitting machine with an SRP60N ribber attached is used. The machine is not suitable for producing an entire formwork for a building element since the size is limited to 200 needles wide and is relativity manual compared to industrial-type knitting machines. However, whatever can be done on the simple machine could be translated to an industrial machine if to implemented on a larger scale.

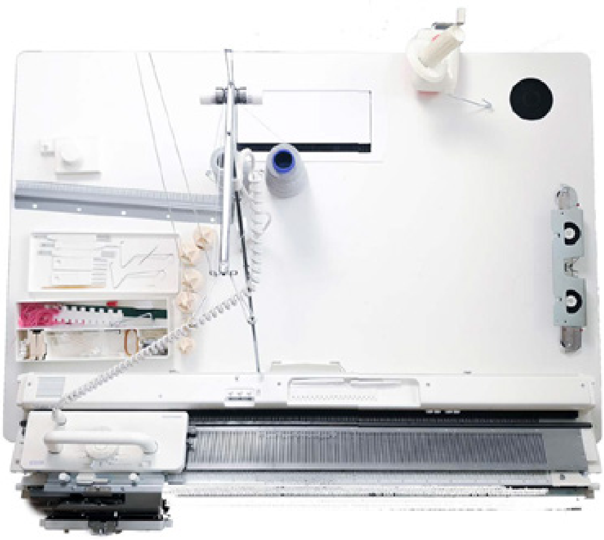


Figure 3.1 Knitting machine set-up

4. Design study

The design process is a tool to examine the knitted formwork for concrete casting in a project setting. A conceptual design for key element is presented at the end of the study. As the study is done in an iterative matter will the resulting design embody the findings throughout the process. The project is done in collaboration with architect student August Sjölin at Chalmers University with the expectation is that architectural values will be reflected in the study.

4.1. Site and constraints for the design proposal

The location of the design proposal is in Gothenburg, Sweden at Södrahamngatan 47. This location is also known as Brändatomten as the previous building was badly damaged in a fire resulting in the need to tear it down. The gap that was left between the two adjacent buildings has since been in the location of many design proposals. The characteristics of the site are that it is very narrow but deep, with dimensions 12 meters by 35 meters. The adjacent building both have a public ground floor with approximately 4.5 meters in ceiling height. The right building is in total 4 stories and the left building 5 stories.

Figure 4.1 Location of design proposal Södrahamngatan 47, Gothenburg

Figure 4.2 Location of design proposal Södrahamngatan 47, Gothenburg

4.2. Methodology

The study is done in an iterative matter and have a research-by-design approach. A large emphasis is on model making. Nervi wrote in *Structures* (1956) that the education for engineers should be focused around model making as this gives a structural intuition, especially form resistant structures. Especially as form resisting structures was not yet a part of the subconscious of our structural thinking. In addition, is knitting in a building environment relatively unexplored making it well suited to investigate with models as the reference base is limited.

Nervi (1965) also emphasized the architectural qualities should not be ignored rather embraced by the structural engineers. As the design study is being done in close collaboration with architect student August Sjölin are the architectural values present throughout the work.

The design study is done in three stages where the scale and level of detail will vary. In the first stage, the emphasis is on the knitted fabric which is examined on a scale of 1:1. This is done in a quantitative matter where a significant amount of tests will result in a large pool of results to draw conclusions from.

In the second stage, the context of the site enters forcing the narrative to broaden. External demands on an architectural scale are the focus, however, remaining in a conceptual design phase.

In the last stage, is a final design proposal presented. The design is still conceptual but with some verifications and quantifications as an indication of the viability of the design proposal.

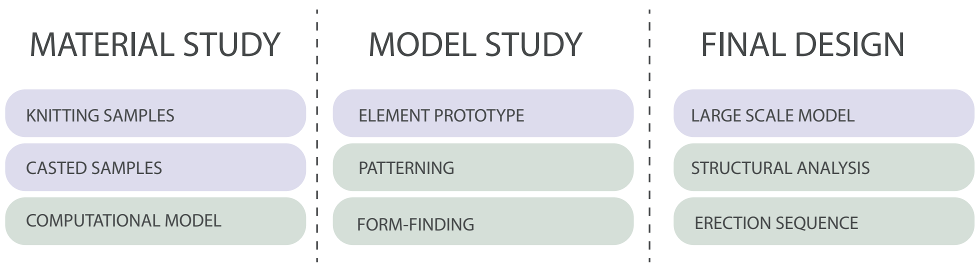


Figure 4.3 Workflow diagram with purple for physical model work and green for computational work

4.3. Material study

In the following subchapters the material study is presented. The focus is on small material tests but on a scale of 1:1 to capture the material behavior and develop a understanding of the structure of the knit and its interaction with concrete.

4.3.1. Knitting samples

A large sample of knittings are produced. The intention of the samples is to get a better understanding of the behavior of the knitted fabric and how it could be manipulated. Some of the knitting samples are presented below with a short comment on the special characteristics of the sample.

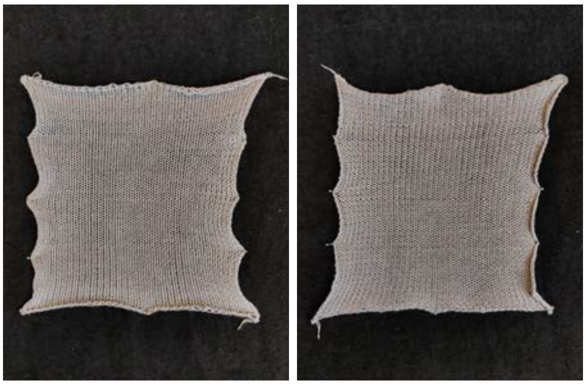


Figure 4.4 Single jersey

Stockinette or single jersey, the simplest knit.

Figure 4.5 Single jersey with drop stitch

Varying density of the knit. The area where loops were knitted on both the main bed and ribber bed and then the ribber loops were unraveled. Adding volume to adjacent loops then gets looser with approximately double the size of the regular loops.

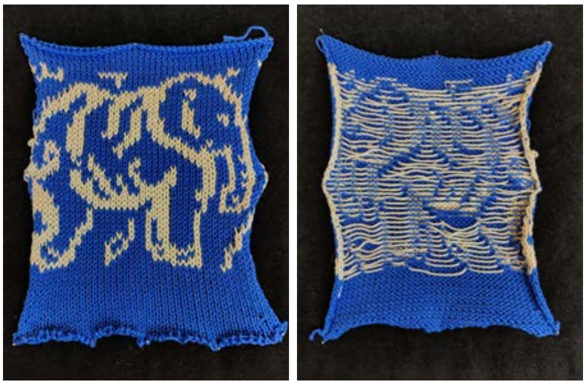


Figure 4.6 Single jersey fair isle

Multiple colored knit using fair isle where the inactive color runs loose on the backside.

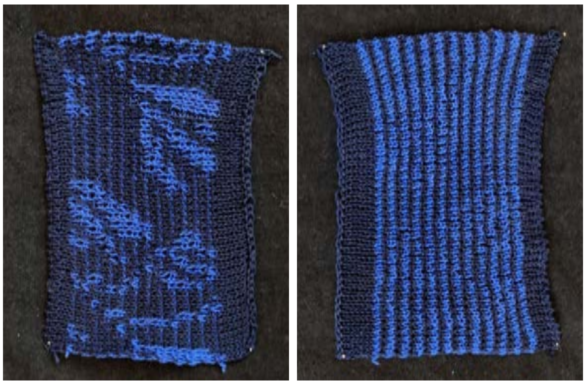


Figure 4.7 Jacquard knit

Much more elastic knit compared to the single jersey, especially in course direction. The knit has a front and back and the inactive color is enclosed between the two layers.

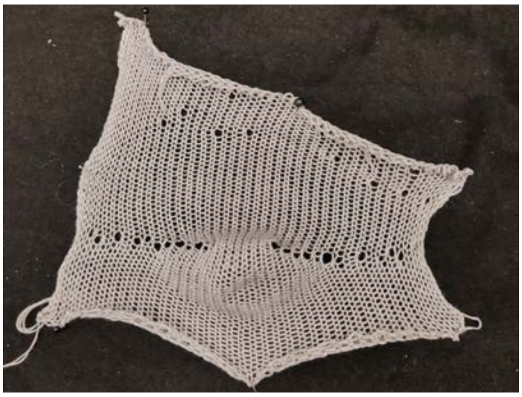


Figure 4.8 Single jersey with slip stitch

The sample has a 3d effect. The area where the stitches are not slipped bulged out of the plane of the knit.

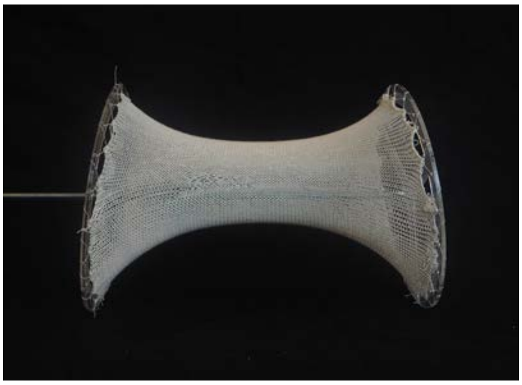


Figure 4.9 Tubular knit, single jersey

The top half was knitted with a higher tension than the bottom half. When the tube was tensioned the frame tilted towards the tighter side which is straighter while the looser half gets more curvature.

Figure 4.10 Tubular knit with drop stitch

The tube was tensioned and become somewhat faceted. Tension bands form where there are continuous strips without drop stitches can be located.

4.3.2. Cast knitting samples

As the intention is to use the knit as formwork for concrete casting, some knitting samples are tensioned in a frame with wet concrete poured into or coated onto. This is done to document the effects on the knit and the finished concrete. The first tests are simple squares with different knitting techniques to manipulate the fabric. In the progression are different geometries tested, both solid models and more shell-like models were produced.

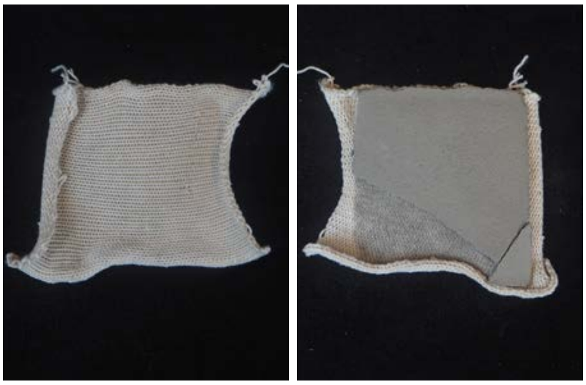


Figure 4.11 Single jersey, every needle

No visible deflection under the weight of wet concrete.

Figure 4.12 Single jersey, every other needle

Significant homogeneous deflection under the weight of wet concrete, some leakage.

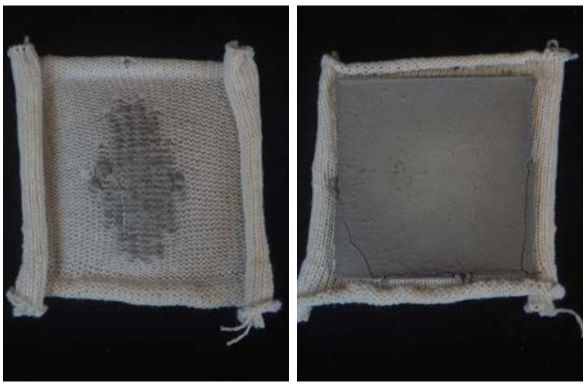


Figure 4.13 Mixing every and every other needle

Homogenous deflection.

Figure 4.14 Drop stitch

Large difference in deflection under the weight of concrete. In the drop stitch area, a bulge is formed. Plastic foil was used to prevent leakage.

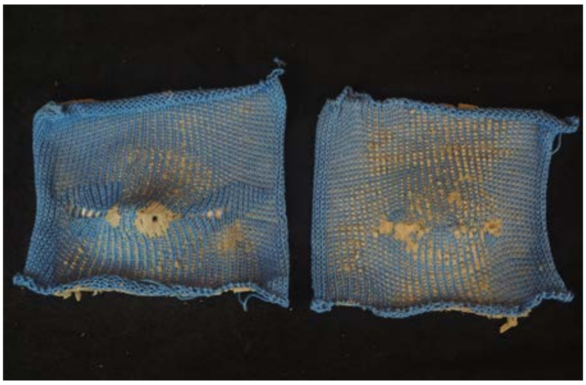


Figure 4.15 Short-rowing

A bump was created using short rowing on the sides. In the first sample, the bump was knitted with double the amounts of rows compared to the second. The bump was reflected in the casted product as well. However, significant leakage in the first slipped loop per row.

Figure 4.16 Crochet

On a single jersey knit tight bands of crocheting are added. The lines are reflected in the casted samples as lines limiting the deflection.

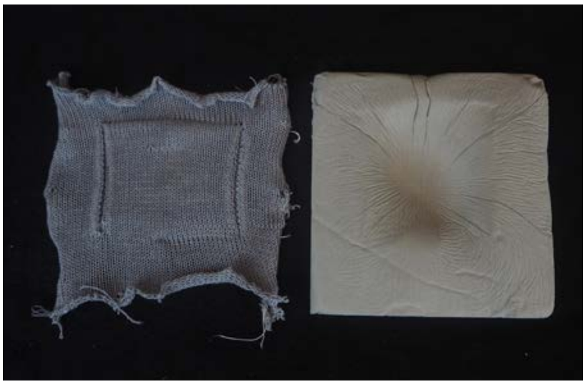


Figure 4.17 Inflated pocket

Pocket on a single jersey where an inflated balloon was added. The balloon is reflected with an indent in the casted sample. The squared perimeter of the pocket is also visible. Plastic foil was used as lining.

Figure 4.18 Partial double jersey

Single jersey with two areas of rib, one with full rib and single rib. The rib reflects in the texture of the concrete sample, however, the deflection is homogenous.

Figure 4.19 Solid model with drop stitch

The concrete adopts the shape of the dope stitch areas where the concrete protrudes more in the less stiff areas.

Figure 4.20 Tube with drop-stitch

A latex membrane is used to pour the concrete into. Areas with drop-stitch are less stiff and do not restrict the membrane to the same extent resulting in a bumpy cylinder.

Figure 4.21 Large square to smaller circle

Four panels are joined to a tube. The formwork is tensioned from top to bottom and cast. The resulted geometry smoothly transforms from a square to a circle.

Figure 4.22 Saddle shape formwork

A wooden laser cut frame is cut. The sides have the same curve but in different directions. When the knit is stretch and fastened by the nails it adopted an anticlastic curvature.

Figure 4.23 Casted saddle shape

A single jersey knit was tensioned in the frame and glass fiber mixed with concrete was placed on the fabric. The result is an anticlastic shell approximately 3mm thick with some variation.

Figure 4.24 Saddle shape with drop stitch

The knit is tensioned in the frame with a highly elastic membrane to prevent leakage. When cast no visible deflection for the drop stitch area.

Figure 4.25 Tubular

Concrete was poured into the tubular knit while rotated for 30 minutes, resulting in a shell tube. The knit is fully embedded in the concrete.

4.3.3. Computational model

Form finding of the knit is done by using PSS, described in chapter 3.2.1. The system was set up in Rhino/Grasshopper using Kangaroo's dynamic relaxation solver that is appropriate for large displacements of non-linear systems. Four different mesh option, seen in Figure 4.26, was evaluated to be the most appropriate to use in a simulation of knitted fabric.

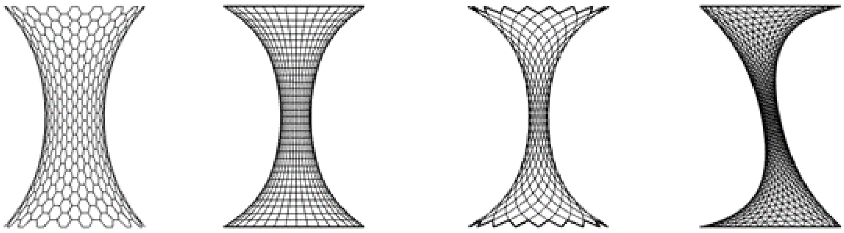


Figure 4.26 Tubular mesh form found with particle spring system where rest-length is set to 10% of original length, a. Hexagon mesh b. Quadrilateral mesh c. Diagrid mesh d. Triangulated mesh

The triangulated mesh warps as the diagonals are not equally distributed. The other three all behaved in a very similar way, with the difference in circumference of the waist. This could also be controlled by the rest length or relative stiffness of the springs. Therefore, is the quad mesh chosen as it is much simpler to map on an irregular surface than for instance hexagonal mesh. It also follows the same logic as the loops in the knit and the mesh can therefore be more direct interpretation. The mesh can be directly translated from a knitting pattern where x by x loops can represent one facet in the quad mesh.

The spring system simulation is applied to recreate some of the material samples with drop stitch. To simulate the added volume in the loops of the drop stitches, the rest length was modified to be double the one for the rest of the mesh. In Figure 4.27 a. the springs are pre-tensioned by giving them a rest length of 0.5 their original length, making the dropped stitches rest length their original. In Figure 4.27 b. is the spring system loaded with pressure to simulating the load of the wet concrete. The results of the simulations is a distortion of the mesh in-plane respective distortion out-of-plane. The result can be compared with casting samples in Figure 4.24 and 4.14.

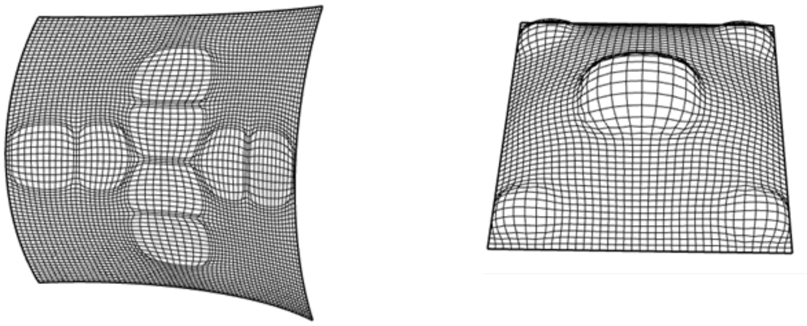


Figure 4.27 Drop stitch simulation with a. in-plane distortion and b. relative out-of-plane displacement

4.3.4. Stretch test

Knitted fabric has two main directions with different stiffness in each direction. In order to evaluate the relative stiffness of the directions is a stress/strain test performed. Two pieces of single jersey of the approximate size of 10cm by 10cm are made. The fabric pieces are fastened on a squared background with one side to the backboard and the opposite a frame along the edge. The frame of the free edge a newtonmeter was fasted and pulled. The stretching of the fabric was measured against the squared 5 by 5mm background with corresponding force measured by the newtonmeter.

The two pieces of fabric were oriented in different directions in order to evaluate the two main directions, measuring the stress/strain in the wale and the course direction. The result is plotted in diagram in Figure 4.28. As can be seen, the material has a non-linear behavior where the initial stretching of the fabric can be done without much force applied. This is to be expected as the loops contract in the perpendicular direction of the applied force. As the loop tightens more linear behavior can be seen as the loop cannot reconfigure in the pediculate direction as much as initially.

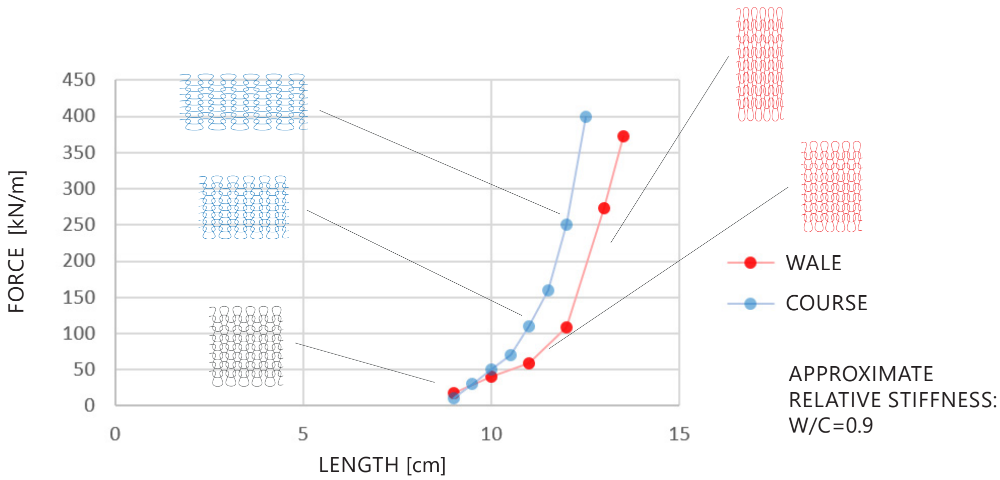


Figure 4.28 Uniaxel stress-strain plot for knitted fabric in course and wale direction

To further improve the PSS simulations is the relative stiffness in the course and wale direction extracted from the test. The approximate value is based on the slope in the later stage of the stretching where the elongation is a more linear. The initial non-linear behavior is reasoned can be discarded as the original state of the knit will be assumed to be after the initial stretching. For instance, will the loop size be based on a slightly stretched sample piece to not account for this when mapping the knitting pattern.

The stretch test was conducted using mercerize cotton yarn knitted with tension setting on 2. For other yarns and settings on the knitting machine would show a different result. The same yarn and similar settings are used throughout the thesis. However, in further development would a more precis stress-strain test for a large number of fabric samples be desirable.

4.3.5. Reflections from material study

It is clear that the knitted fabric can be manipulated in many different manners. Shape, density and stretch are some of the ways that the knit properties can be changed. The properties are also often intertwined not least the density and the elasticity. As seen in Figure 4.11 and Figure 4.12 is the knit of every other needle compared to every needle much more flexible and deflects significantly. The looser, less dense knit is also the one with the most stretch. The opposite relationship can be seen in the jacquard knit where the density is almost that of two fabrics but also significantly more flexible than that of a single knit. As the jacquard knit is structured more like a full rib where the yarns run back and forth between the main bed and ribberbed. This can be seen in the fabric as it has two right-facing sides and will add length to the yarn. However, this length is mostly added in the course direction making the jacquard significantly more flexible in that direction but with similar stiffness in the wale direction as a single jersey.

One key difference in the manipulation is the difference in global and local geometry. The global properties are how the overall geometry of the knit acts under for instance the pressure of fresh concrete or when tensioned. The local is where the geometry can deviate from the global geometry. One example of this is in Figure 4.14 where the area of the drop stitch is bulging out, interrupting the global geometry. Such effect can not be seen in Figure 4.13 where the loose, every other needle knit is mixed with the tighter every needle knit. The result is instead a homogenous deflection where no local effect can be seen between the two areas. The difference between a loose-knit and drop stitch knit is that the loop size is larger for the drop stitch in both course and wale direction whereas every other needle volume is only added in the course direction. Volume needs to be added in both directions as the stiffer direction will otherwise act as the main load-carrying direction making the tension in the other direction less important. This conclusion can also be supported by observation from Figure 4.18. Where the ribbing is adding volume again in course direction without seeing any local deflection.

Short-rowing, seen in Figure 4.8, proves to be an efficient way to create curvature within the knit. The local geometry can be changed by having additional rows in certain areas. However, as seen in Figure 4.15, can drastic changes in the geometry create strain localized in a single loop. Leading to the conclusion that short-rowing is well suited to shape the global geometry that often has a more gentle curvature. While more drastic local geometry should be done with some care.

Other knitting techniques of interest moving into the next stage considered are the inflated pocket and drop stitch as they in contrast to short-rowing displays the ability of locally impact the geometry. The air pocket and drop stitch show inverted results as one removes concrete by making an indent and the other adds material by protruding out.

By comparing the figures from Chapter 4.3.3 with corresponding knitted samples in Chapter 4.3.2 the conclusion can be drawn that the PSS can be used successfully as a simulation for knitted fabrics. Further development is to implement the stretch test to the PSS. Since the stretch test was quite analog and not very precise should the values extracted not be used for any detailed analysis. However, it could inform the PPS of the relative stiffness in the course and wale direction to calibrate that model somewhat.

4.4. Model study

In the following chapter is the second iteration of the design study presented. The focus is to translate the findings from the material study and apply that knowledge to elements. The context of the site and other external demands enters at this stage.

4.4.1. Structural element

When using pre-tensioned knitted formwork, the consequence is that the element gets an anticlastic shape as this is how tension only membrane works. In order to explore the design space are some initial shapes generated using quadrilateral mesh and PSS system with zero-length elements. The result can be seen on the next page where an intuition of the design language can start to develop.

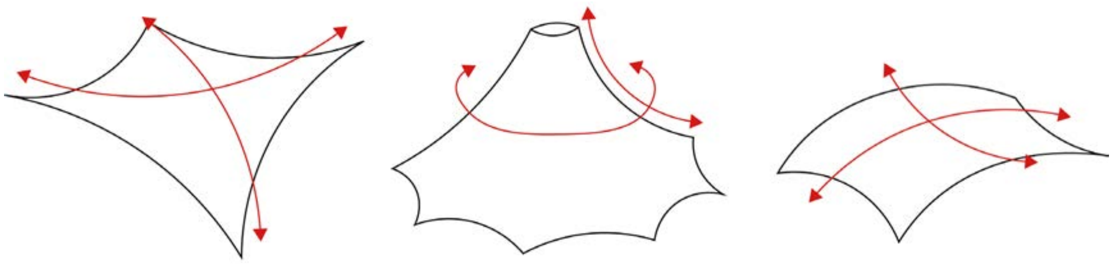


Figure 4.29 Anticlastic shapes A. Hypar B. Coinic C. Barrel vault

Moving forward will the "umbrella" structure be used, where a single column expands out to a slab. The structure has the potential to fully demonstrate how knitted formwork can be used.

Listed below are the reasoning for why the umbrella structure is considered the strongest candidate:

- Produce a "complete" independent structure as one unit.
- Utilize the existing boundaries (walls and floor) to tension the formwork.
- Complex and very large formwork if using traditional casting methods.

In addition to the umbrella structure will a "half column" element be used. This element will be used to implement ribs in the shell structure. The half colum is used out of practical reasons since the back is easily accessible and a similar formwork as seen in Figure 4.22 can be used to produce it.

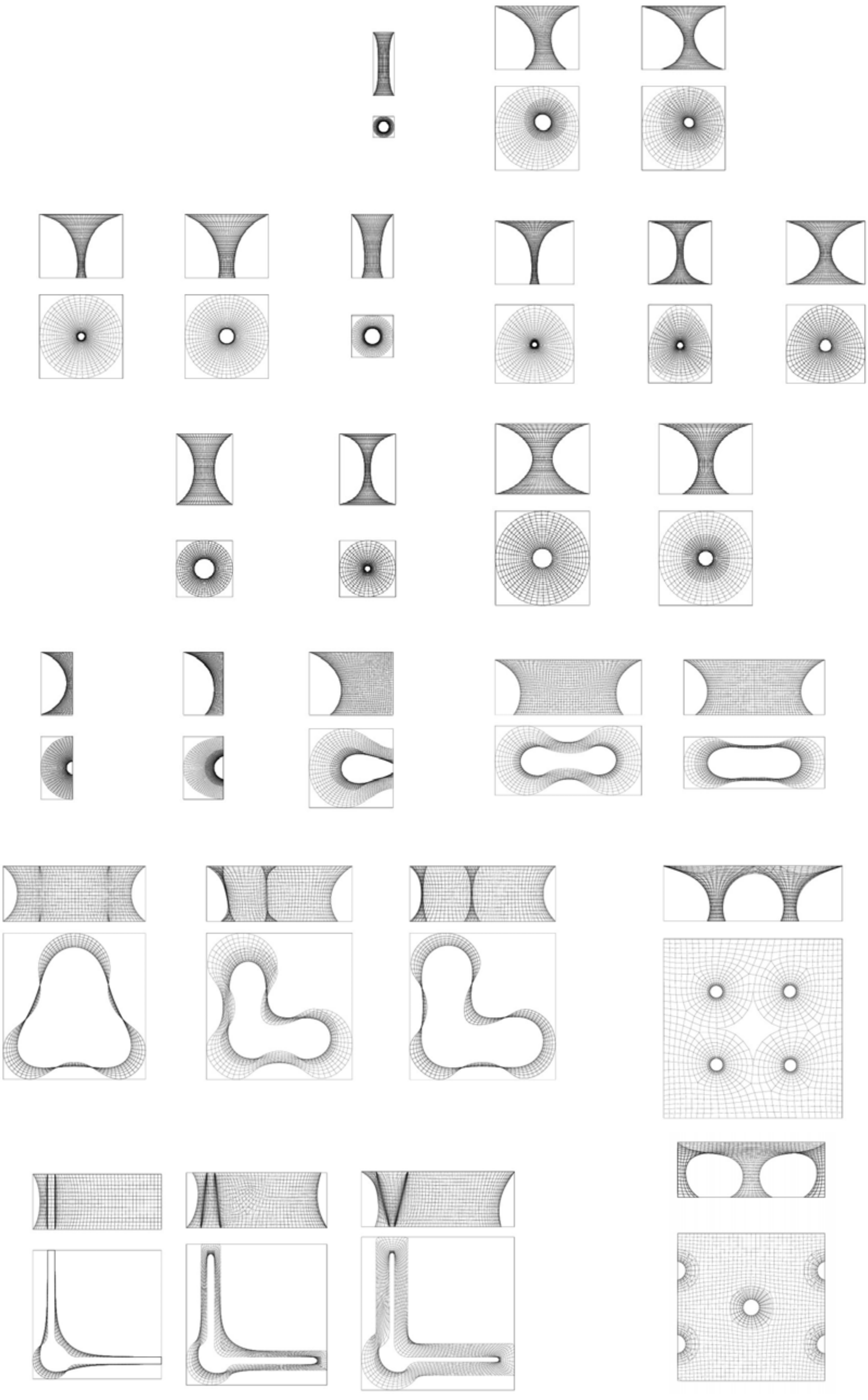


Figure 4.30 Element design options generated using PSS with zero-length elements

4.4.2. Structural concept

The umbrella shape is intended to work as a shell structure in predominant compression. Form finding using stretching of fabric for shell structures has been done before for instance in the Ponte sul Basento bridge. The points where the fabric is being pulled are in the finished structure where the load is applied, going from a fabric in tension to a shell in compression. Here the load from the bridge girder is considered to be the dominated load and the self-weight of the shell superstructure negligible in comparison.

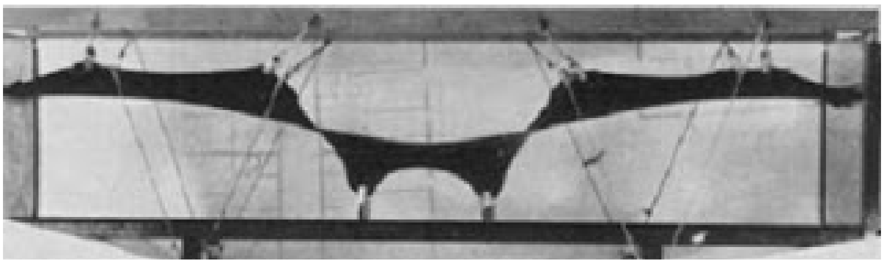


Figure 4.31 Sergio Musmeci, Bridge on the Basento river, physical models and realization, 1974.

In the umbrella structure fabric is not only used to form-find but also as formwork. When tensioning the formwork, the resultant force should be inverted to compression when the shell is cast. As the gravity load is not angled a third horizontal force will complete the equilibrium. As seen in Figure 4.32 the gravity load will be balanced with compression in the shell and tension in the slab. As the slab is flat and not doubly curved like the rest of the structure this will be easier to reinforce to carry the tensile forces.

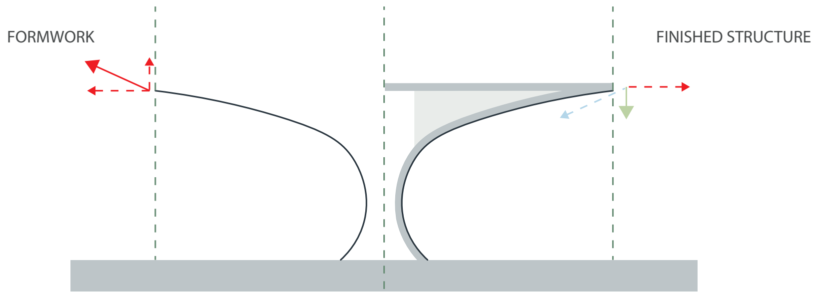


Figure 4.32 Sketch of structural concept

4.4.3. Shaping knitting pattern

The knitting pattern generated using the open-source tool from ETH Zurich in Chapter 2.2.3 is not optimal for the knitting machine available at Chalmers University. A custom script for knitting patterns is produced that considered the limitations of the SK840 knitting machine. For shaping the geometry is only short-rowing used and not moving, decreasing, or increasing the number of loops, since these operations needed to be done manually. Manually operations are very time-consuming and likely to attract mistakes due to the human factor. Short-rowing on the other hand could be done automatically using the interactive software DesignaKnit8.

The pattern is generated by dividing the top and bottom edge curves based on the loop height. The points on the bottom curve find the point on the top curve that will generate the shortest path on the surface. These lines are then divided based on the loop width. The distance between neighboring points is calculated and divided again based on the loop height. First, the straight segments are generated by the rows which contain the same number of points. Then the branching paths are generated by the shortest segments that will continue the path. Step by step is seen in Figure 4.34.

In Figure 4.33 the shape of the umbrella model. The pattern was generated in three pieces with the knitting pattern for the top part visible. Each line is in a color that represents the length and number of loops for that row. The pattern is constructed so that each line represents two rows of knitting. This is done to eliminate yarn to run loose which it will if the row doesn't start in the same position that it ended.
The generated knitting pattern is also later used as a mesh to represent the knit. When generating the mesh the loop size is not relevant but instead, the size input represents how coarse the mesh is. For the mesh representation both the branching elements are used not only the shorter one as the loop is connected on both sides and would otherwise cause a hole in the mesh.

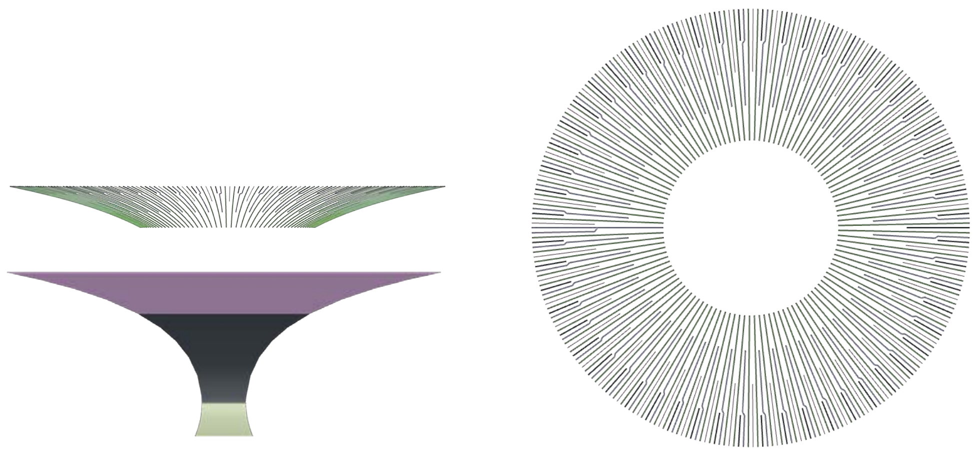


Figure 4.33 Pattern for top purple part of model

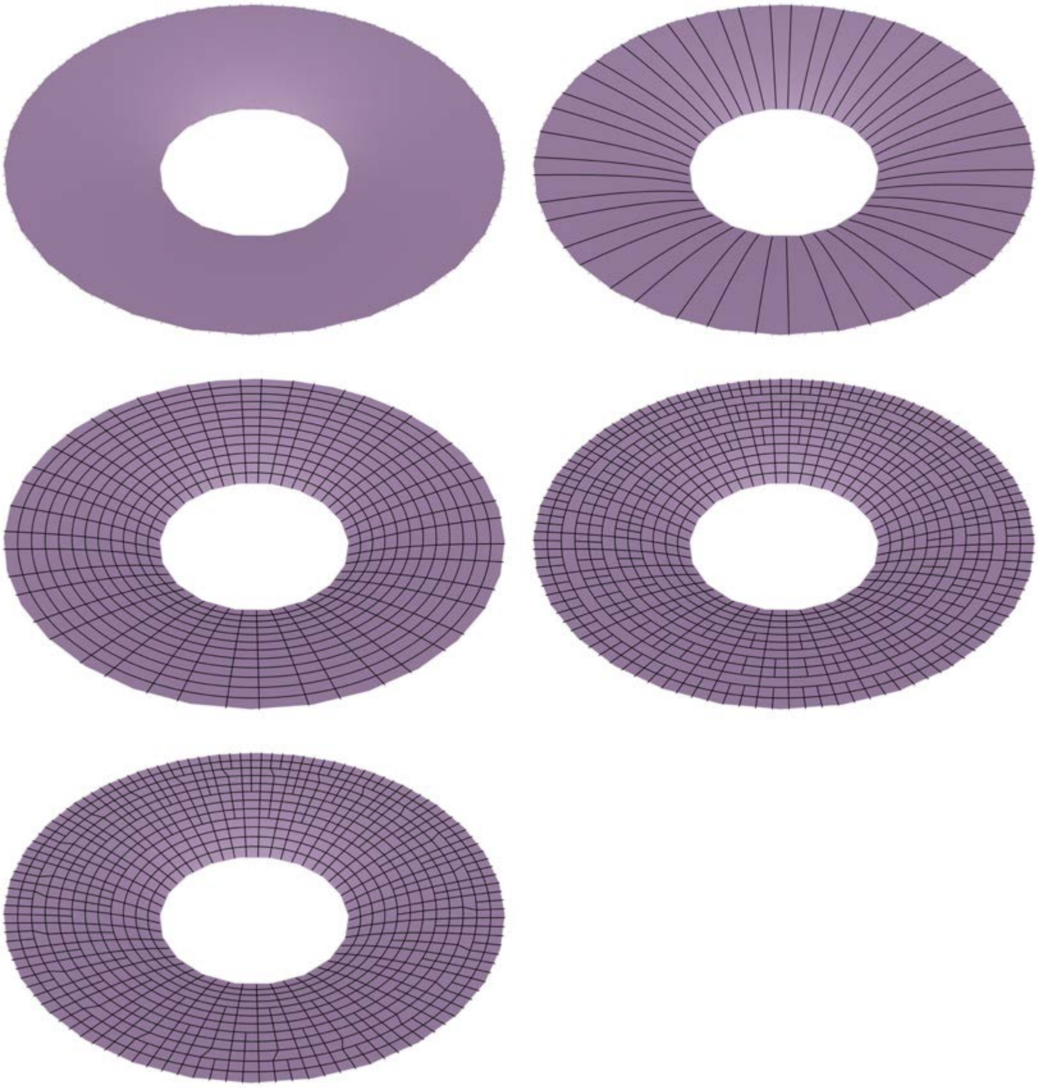


Figure 4.34 Step-by-step pattern development

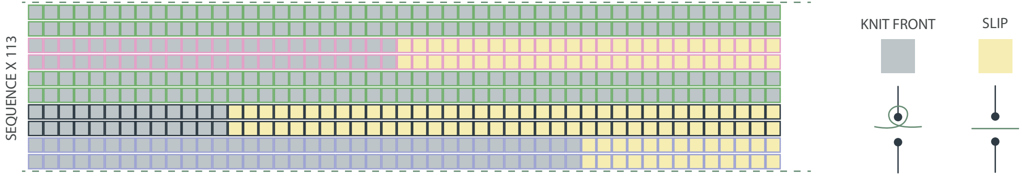


Figure 4.35 Pixel pattern for top part of model

4.4.4. Model of umbrella structure

The formwork for the model is knitted based on the geometry seen in Figure 4.34. The three pieces are sewn together using the same yarn as it was knitted in. To tension the fabric a falsework system was made. It consisted of a circular frame with holes that are laser cut in plywood. The frame is constructed by overlapping segments to minimize the waste and mounted on threaded rods. The formwork is fastened in the bottom and the top by small nails penetrating the knit and locked in the predrilled holes. Finally, is the knit tensioned by the nuts, sliding the frame along the threaded rods.

The concrete is mixed with glass fiber cloth to lock the paste. The intent was to prevent leakage and use the cloth to build up the depth since the concrete mix was quite fluid. However, as seen in the result in Figure 4.37, is there some leakage. The source of the leakage is primarily where the short rowing ends and bigger wholes are created. In the line of short rowing where the curvature goes from close to straight to the start of growing outwards, there's significant leakage. Some wrinkling of the knit can be observed in this area.

As this is the first iteration of constructing something more similar to a complete element was the final size difficult to predict. The knit geometry is based on a model 1:40 where the span was 12m and the height 4.5m. When the fabric had been stretch to what was assumed to be stiff enough to not deflect significantly during casting is the scale about 1:30. However, the proportion changed somewhat, growing more in height than span length.

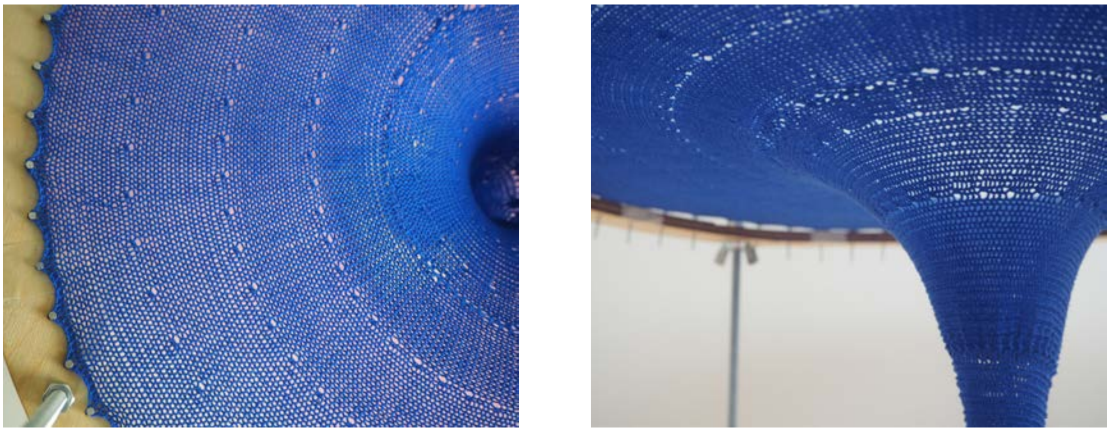


Figure 4.36 Tensioned formwork a. top view b. zoom on wrinkles.

Table 4.1 Proportions of model

	Span [mm]	Height [mm]
Before tensioning	300	112.5
After tensioning	400	190
Difference [%]	133%	169%

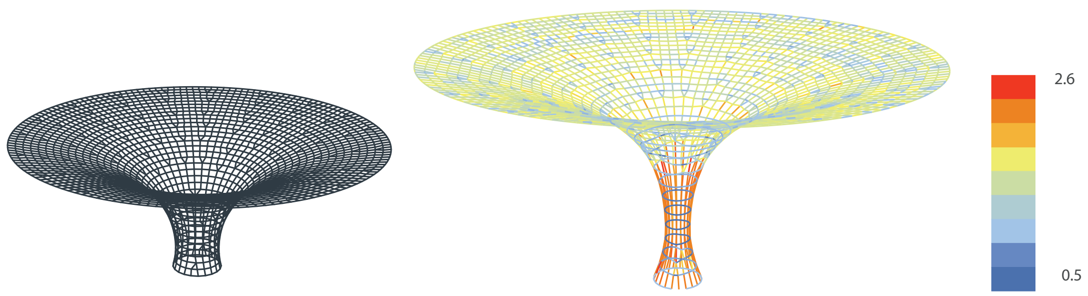
Figure 4.37 Tensioned formwork to finish casted umbrella structure

4.4.5. Comparison between digital and physical model

The digital model used to create the knitting pattern is also used to create a PSS model. A mesh was generated using the knitting pattern script however a much more courser mesh than for the patterning. The mesh is also made squared as the properties in Chapter 4.3.4 are per unit length not per unit loop. Each mesh edge was represented by a spring that was connected to neighboring edges. The stiffness of the springs was informed by the test in Chapter 4.3.4, making the springs in wale direction 0.9 of the stiffness in course direction. The rest length is set to zero for all elements.

In the physical model is the knit fastened in the bottom plate and stretched to the frame. To simulate this stretching are fictional springs modeled between the edge of the knit to the frame. These springs were modeled significantly stiffer than the knit and set to rest length zero. Since the springs are much stronger than the knit will these springs contract forcing the knit springs to stretch to the frame.

The model oscillates into the final geometry where the system is in equilibrium. The spring length of the stretch and original model was compared and is shown in Figure 4.38. As can be seen is the trunk stretched in the course direction while contracted in the wale direction. The yarn has redistributed removing from the height of the loop and added to the width. In the top part is the elongation is more equally distributed between course and wale direction.



ORIGINAL MODEL AFTER SIMULATING STRETCHING

Figure 4.38 PSS model initial state and final

As measurements on a doubly curved surface can be difficult to retrieve are two measurements retrieved from both the digital- and physical models to check their coherence. The diameter of the thinnest part in the trunk and the length of the geodesic from the base to the top are noted in Table 4.2.

To be able to reflect on the significance of the measured values from the stretch test are additional PSS simulations made. In each model is the ratio between the stiffness in the course and wale direction adjusted and the measurements are collected. The result is presented in Table 4.2 where it can be seen that the values do influence the geometry. Increased stiffness in the wale direction contracts the knit as where increased stiffness in the course direction opens it up.

Table 4.2 Mesurments from PSS

Digital	Model 1	Model 2	Model 3	Model 4	Model 5	Physical model
Stiffness course	1	1	1	1	1	-
Stiffness wale	2	1.1	1	0.9	0.5	-
Diameter [mm]	6	16	18	20	33	20
Length [mm]	329	314	312	309	293	315

4.4.6. Eigenmode pattern redistribution of mass

To evaluate the parametrization technique of eigenmode vibration patterns is an half column element used. The element is form-found using a PSS and parametrized using the vibration eigenmodes. The pattern from the eigenmodes is used for to redistribute the mass, where the darker areas are thicker and therefore stiffer compared to the lighter. The distribution was done so the total mass of each element is the same, with the average thickness of each element is 4.5cm.

The performance is evaluated using linear elastic analysis only looking at the maximum deflection for the same load. The homogenous shell has a deflection of 10mm. An improvement of 10% with a deflection of 9mm with the redistribution of mass using mode 3, with the thickness varied from 3cm to 6cm.

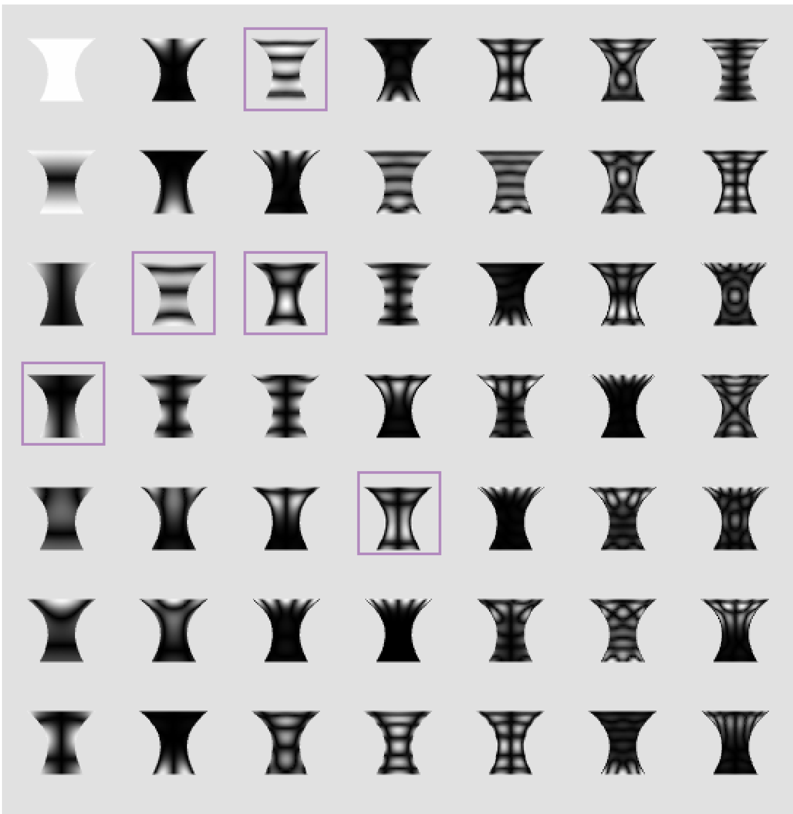


Figure 4.39 50 first eigenmodes pattern for the wall element with the five best preforming patterns with regards to stiffness marked.

4.4.7. Model with inflated pockets

To redistribute the mass in shell structure using knitted formwork can the knit preprogrammed with pockets. In the pockets, balloons are inserted and inflated to the desired thickness. Indents are created by the balloons, forming ribs between the pockets.

Pattern from the eigenmodes that had the highest stiffness for the governing load case could inform the placement of the pockets. The shell would then have a rib pattern that reflects the eigenmode.

The resulting geometry could, if chosen the right mode, have increased stiffness. The reason for using vibration modes is the fast parameterization of the surface. In addition are the pattern themselves very visual and contributes to the architecture as an ornament.

The pockets are constructed by using the second needle bed, the ribbener. While the carriage travels left the needles on the main bed are knitted. When the carriage travels right the needles on the main bed are again knitted except in the pocket area. In this area, the needles on the ribbener bed are activated and knitted. This results in the pockets being knitted with half of the rows compared with the rest of the knit. A result of the pockets being knitted on the front when carriage goes left and back when going right as to the rest is knitted no matter the direction. This could be avoided using a machine that can have several yarn carriages with one yarn knitting the back of the pocket and one knitting the whole front of the piece.

If only the back was knitted going right when there's only one yarn carriage would result in lose yarn string in the back. The yarn would go from the end of the last row to the start of the pocket in the middle of the knit. The first loops would not be properly tensioned when the yarn runs loose, similar to that Fair Isle knit in Figure 4.6.

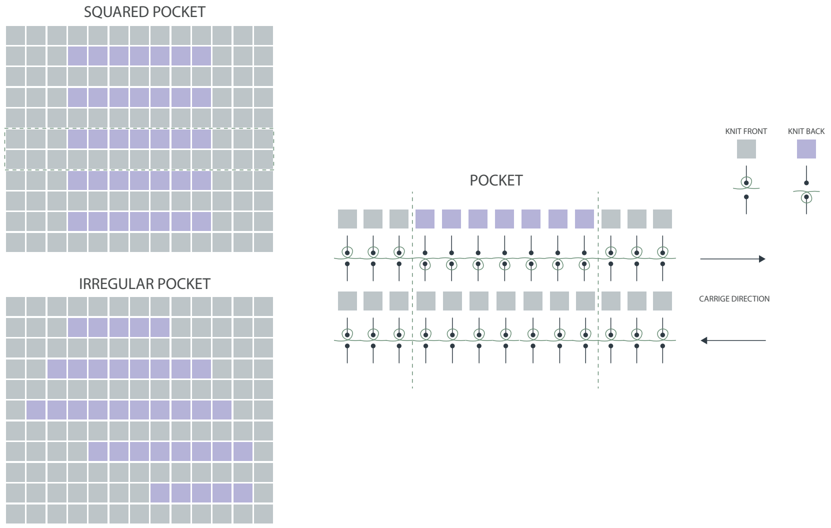


Figure 4.40 Illustration of knitting sequence for pockets

As a first iteration is a knit with three squared pockets constructed. The tension for the knitting machine needed to be lowered resulting in a less dense knit. This was necessary since as when using the ribbener the machine struggles when the fabric is tight and the opposite-facing needles are used. A wooden frame is used to tension the fabric similar to previous tests. The pockets are fitted with balloons and inflated.

The casted result is stripped of the fabric. The balloons made large indents, showing both the outline of the balloons and the pockets. Overall geometry has a clear doubly-curved shape from the frame as the knit is not shaped using short-rowing.

Figure 4.41 First iteration of half column with air pockets, scale 1:20

Figure 4.42 Second iteration of half column with air pockets, scale 1:20

For the second iteration is the pattern of the pockets loosely based on the eigenmode pattern. The pockets are both more irregular in geometry and size. The same technique of constructing the pockets and same frame to hold the formwork is used. The pockets were smaller which made it more difficult to inflate the balloons as the knit restrained them from expanding.

The resulting shell again reflects the balloons. However, in the second iteration, the result is more smooth where no clear distinction between pocket and balloon. Likely a result of smaller pockets and less sharp corners.

4.4.8. Reflection from model study

As seen in Chapter 4.4.5 seems the PSS to be a rather reliable tool to predict the knit deformation during tensioning. As material properties are unknown only relative values are used. The umbrella shape deformed significantly during tension making the PSS particularly useful as it can be used to predict the final shape. As can be seen in Table 4.2 does the measurements from the physical model compared to PSS model quite close. The diameter is the same for the physical model when using the relative stiffness from the stretch test. However, the base to the top length is not as precise as it is more similar to model 2 with stiffer wale direction. Since the trunk is more sensitive will the measured values be kept, as the base to top measurement is only off by less than 2% for model 4 makes it still a very reliable result.

As for the ribs shaped from balloons are the early results promising. To get a more rib-like appearance will the balloons have to be more closely spaced. However, it could be a method to achieve a shell structure with increased stiffness to resist buckling or non-symmetric loads, as seen in for instance Palazzo dello sport by Nervi. The ribs would increase stiffness with less material than if the shell thickness was increased homogenous.

The vibration eigenmodes parametrization seems like an effective way to place the ribs in this first iteration. The parametrization technique generates many options select from rather quickly, in comparison if other grid systems were to be superimposed on the complex surface. The gradient of the thickening of the shell is also similar to the result using balloons in the casting as there is not a hard kink between shell and rib. It also gives an interesting visual effect that can de an ornament for the structure in addition to increased stiffness.

As seen in Capture 4.4.4 can an umbrella structure be shaped by knitted formwork. The falsework is custom made which creates some issues. Firstly, will this result in additional waste from the production as custom elements cannot be reused in another project. Secondly, is the tolerance very small as the knit needs to be stretch to the rigid frame and if the fit is not perfect will the formwork either not be tensioned properly or not reach the frame. Progressing in the next step of the design study will the production be developed to avoid such issues. The rib shaping will also be developed to come closer to the desired outcome.

4.5. Final design

For the final iteration of the design some verifications were done. Large scale models and FE-analysis of the shell structure are used to evaluate the feasibility although remaining in a conceptual design.

4.5.1. Concept of structural system

The structural concept of the single umbrella element is presented in Chapter 4.4.2. The emphasis is to ensure that the fabrication method is reflected in a beneficial way in the design. Where the force to pre-tension the formwork is inverted into compression in the umbrella and tension in the slab. Since the slab is flat can it easily be reinforced using rebar mesh. The umbrella will instead be reinforced with fiber mixed in the concrete. Even if there are no significant tensile forces will the fiber control cracks and increase the ductility of the concrete.

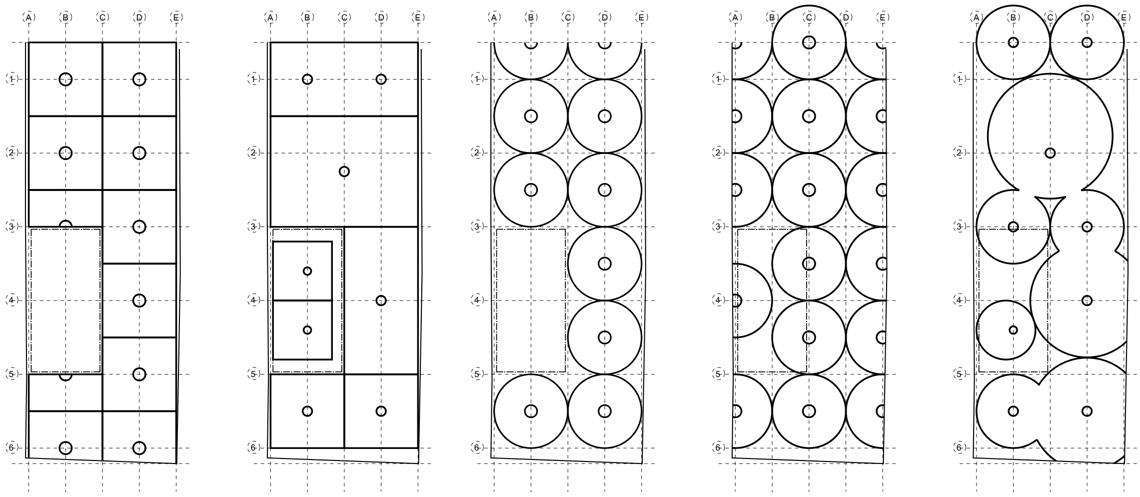


Figure 4.43 Floorplan options consisting of squared or circular umbrella structures

In Figure 4.43 can iterations of the floor plan be seen. The plan is of the second level intended as an office space. The ground floor is intended as a lobby in combination with a bar with an atrium on the left side. The floor plans consist of circular or squared umbrella structures placed in different configurations. For the structural analysis will a circular umbrella that will span the whole width of the building be used to verify the largest possible span for this building.

Since the proposed building rests in between two existing buildings will the horizontal stability be relying on them. The levels would have to be aligned and the floor slab of the existing building would have to be checked if they have the extra capacity to absorb the horizontal loads from the new building.

For the vertical load will the umbrellas of each floor aligned on top of each other. A continuous line will carry the load down to the foundation. This is important since shell structures are sensitive to point loads. Therefore should the column line be kept intact.

The topology of an umbrella structure has been used in many projects. However, there are not as many built references of creating several levels using umbrella structures. However, in Frank Lloyd Wright's Johnson Wax Building some areas have as many as three levels of stacked umbrella columns. The section shows the same logic of having one continuous line down to the foundation. The columns are tapered, coming down to almost a single point revealing that the columns do not take any horizontal load either. From the interior images, umbrellas can be seen connected stabilizing each other and leading the horizontal loads to the facade where the load can be transferred to the ground.

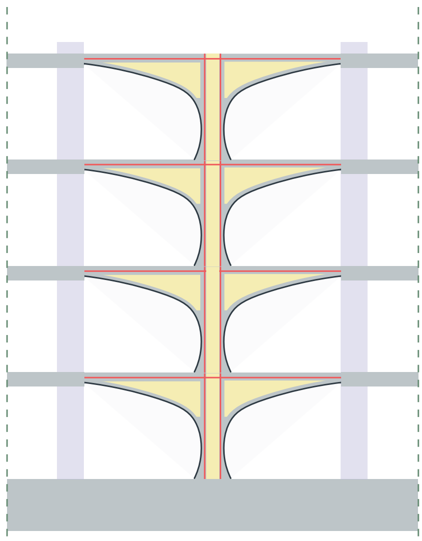


Figure 4.44 Sketch showing the section of stacked umbrella strucutures.

Figure 4.45 Frank Lloyd Wright's, Johnson Wax Building interior and section, 1936

4.5.2. Fabrication of element

In Figure 4.46 is a general fabrication sequence of how the manufacturing of an element presented. The geometry is split into pieces small enough for a CNC knitting machine to produce it. A pixel pattern is generated and the knitting machine can produce the formwork. Shipped to site the formwork is assembled and tensioned and casting can begin. Since the fabric is so light is the transport of such a formwork much cheaper and simpler than a traditional timber formwork.

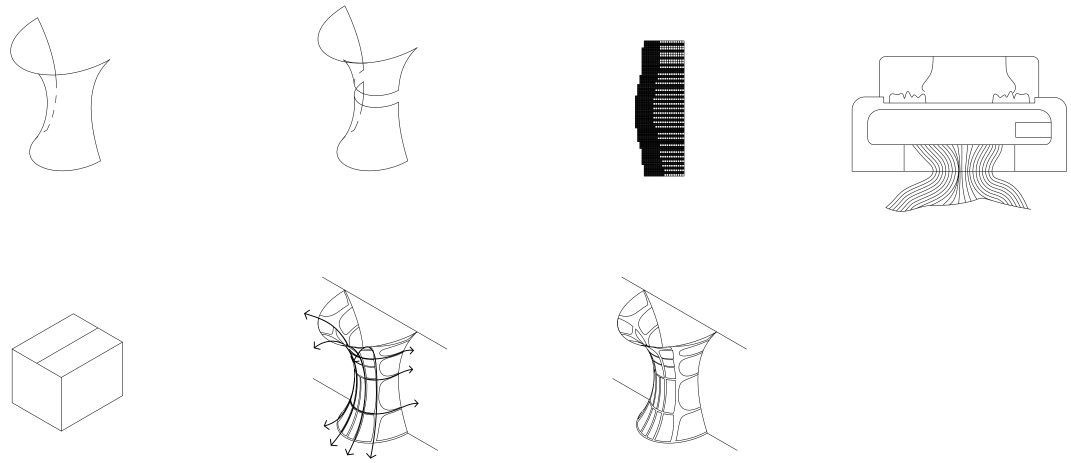


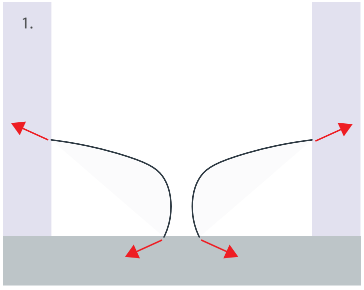
Figure 4.46 Fabrication sequence

4.5.3. Erection sequence of umbrella

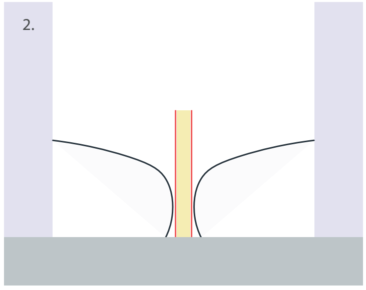
The specific element of the umbrella structure is presented in this thesis and studied more in detail. A challenge here is to produce a flat slab on the top of the element as the building consists of several floors. In order to do so, the casting process is done in stages and presented on the next page.

The casting process takes advantage of the properties of the knitted fabric. The lower part of the trunk would be difficult to cast if the fabric was not permeable as air would get trapped flared bottom. Since the hydrostatic pressure will peak in the bottom in the combination of the air permittable formwork will ensure high quality of the concrete without air bubbles. This is also important if the concrete is to be stripped of the formwork that the finish of the concrete is not compromised.

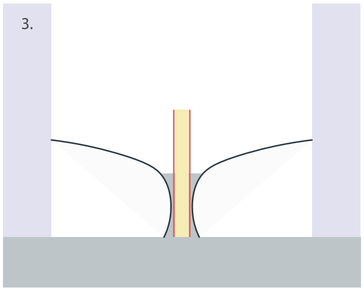
Since the different parts of the concrete need to be fully connected will the casting process be done in one session. This puts high demand on the knit as it would need to carry the load of all the fresh concrete. An alternative casting process would be to let the umbrella harden before casting the ribs and slab. This could limit the demand of the knit, however, the shell would have to be checked if it can carry the load of the slab without the tension tie that it forms when hardened. It also demands some connection stubs between the umbrella and the ribs.



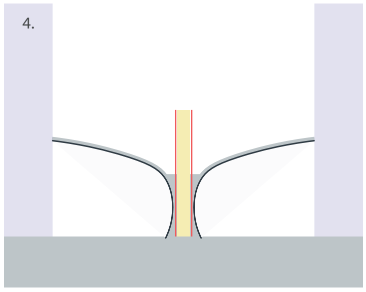
1. The formwork is brought on-site and tensioned. The tensioning is either by using the surrounding environment or temporary scaffolding.



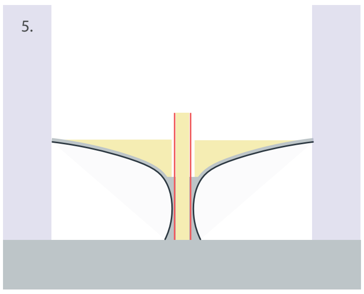
2. A channel and reinforcement cage is placed in the middle. The channel can be used for ducts and electrical wires whereas reinforcement cage is for nonsymmetrical loads in the trunk.



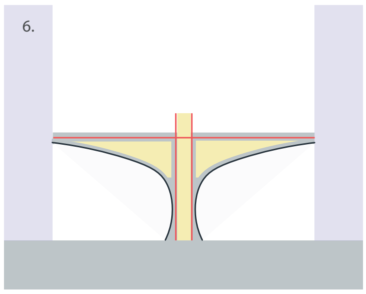
3. The trunk is filled with concrete, where the hydrostatic pressure ensures that all cavities are filled. The permittable fabric allows air to escape.



4. The top of the umbrella is sprayed or coated with concrete to get a thin shell as this surface is more accessible.



5. Foam is placed as void fillers. The spaces between the foam create ribs that will carry the load from the slab down to the shell as well as stiffen the structure.



6. Reinforcement is placed on top of the foam and the slab is cast. Creating a leveled floor that also works as a tension tie for the shell.

Figure 4.47 Erection sequence for umbrella

4.5.4. Model study of umbrella fabrication

To verify this erection method, two large-scale models were produced. One in scale 1:10 of the umbrella structure that measures 0.8m wide and 0.45m in height, and one in scale 1:5 of a shell with ribs that is 0.9m high and 0.7m wide.

The umbrella model is produced as close to the real casting process would be. The formwork is knitted in one piece using short-rowing to add volume to the top. One seam had to be done by hand to close the fabric. The weight of the fabric was 420grams.

A problem that was recognized in the smaller scale models was the tolerances. When the fabric is stretched to a rigid frame the tolerance for the fit of the fabric is limited. If the knit is too big the forwork will not be tensioned properly. In the other case where the formwork is too small, it will not reach the frame. To address this problem is a channel integrated at the top of the formwork. In the channel, is a rope placed and custom-made 3d printed clips are slid onto the knitted channel where the rope lies. The clips grip the rope without pricing the knit. Each clip has a rope that will be tied back to the frame.

To create an edge is a second channel integrated with a smaller wire inserted. After tensioning the formwork is the edge erected by tieing it back to the clip, Figure 4.48d. These clips are not necessarily custom-made, rather based on fasteners commonly used in membrane structures. These fasteners are not commercially available and therefore manufactured using 3d printing.

Figure 4.48 a. Foam void filler b. Formwork being knitted c/d. Sliding clips on and tensioning

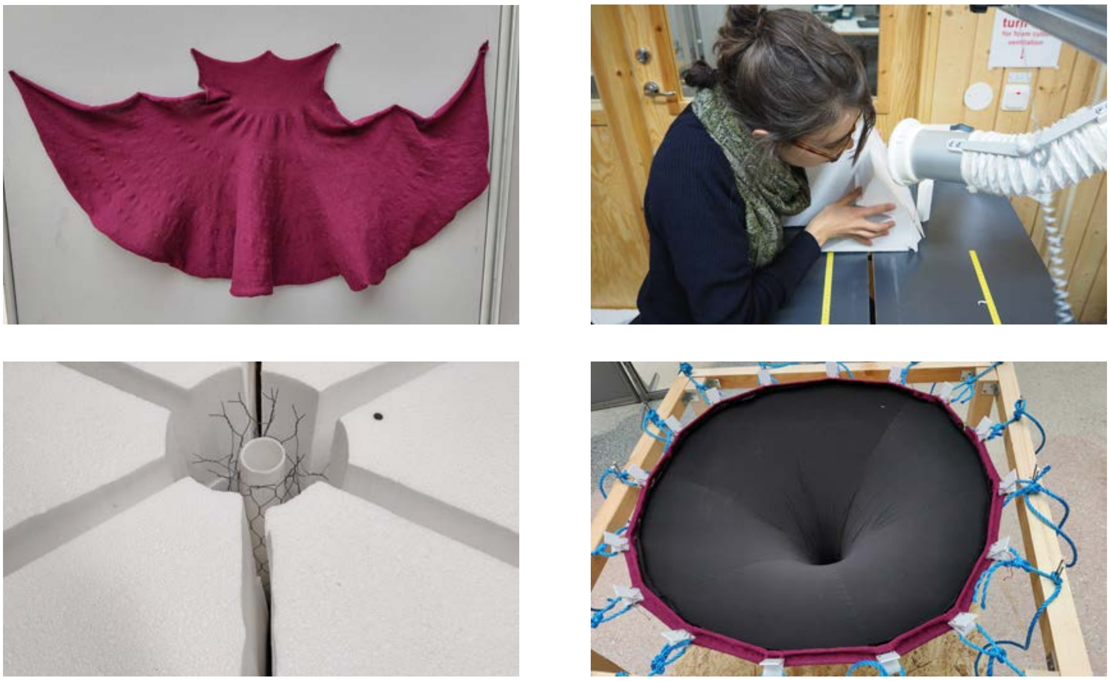


Figure 4.49 a. Formwork before being sewn together b. Making of foam pieces using hot wire cutter c. Zoom on foam pieces d. Liner to prevent leakage during casting

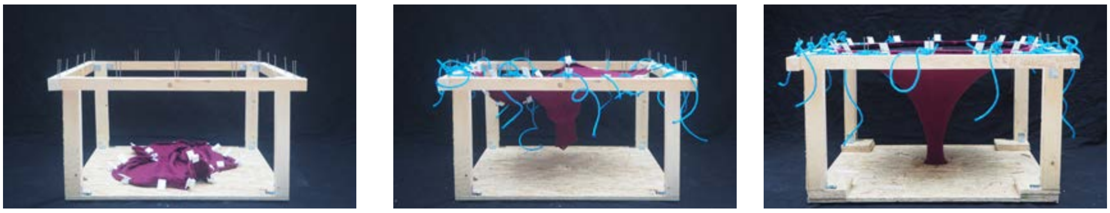


Figure 4.50 Tensioning of formwork in "scaffolding frame"

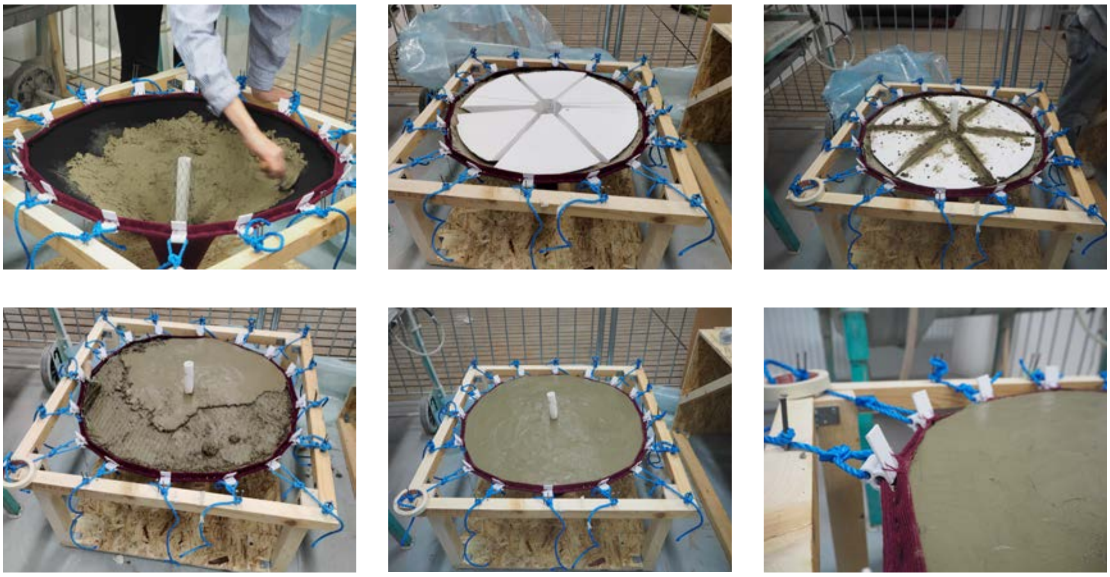


Figure 4.51 a. Coating of umbrella b. Placement of void filler and casting of ribs c. Placement of top reinforecment d. Casting of slab e. Finished cast umbrella f. Zoom of edge of slab.

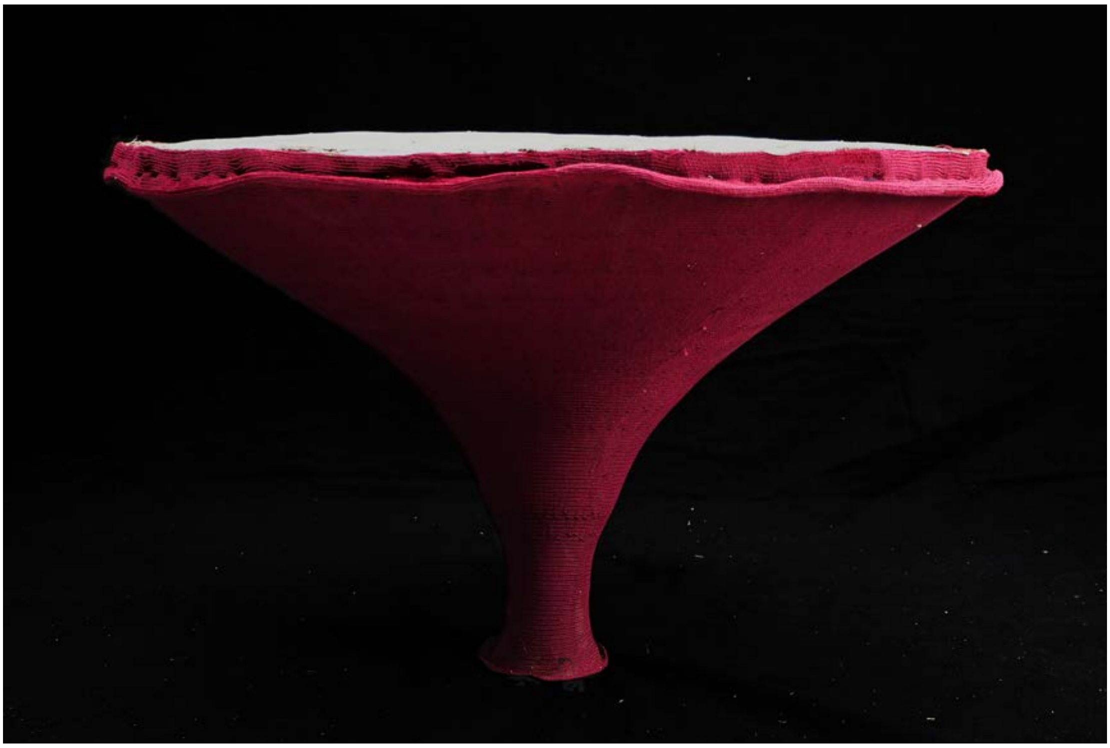


Figure 4.52 Finished model scale 1:10

For the 1:5 scale model, the main focus is the ribs. The same geometry as for the 1:20 models is used. The geometry used to produce the knitting pattern is scaled by 10% to ensure that the knit will be tensioned when stretched in the falsework. The geometry had to be split into three separate pieces due to the limitation of the width of the knitting machine.

Previous models with ribs/indents have the formwork been square with integrated pockets. The integrated pockets can not be produced simultaneously as a double-curved surface since the short rowing would connect the front and back of the pockets. Instead is two layers of the formwork produced and the outline of the pockets stitched by hand. If an industrial CNC knitting machine had been used the formwork could have been produced in a single knit. The pattern for the pockets was loosely based on an eigenmode pattern. Since the focus was the production and the result would not be load tested was the pattern was based on aesthetics rather than stiffness.

Regular balloons are inserted in the pockets and inflated. The falsework was constructed out of wooden particle board that is tailored cut and the edges are lined with small nails, approximately 2cm apart, that the knit was threaded on. This falsework did not consider the tolerances and would therefore not be suitable for full-scale production. Piercing the knit is also a huge risk as it can easily damage a loop causing a chain reaction unraveling the neighboring loops. The formwork was coated with concrete approximately 3cm thick. The concrete is left to harden before stripping the shell of the fabric.

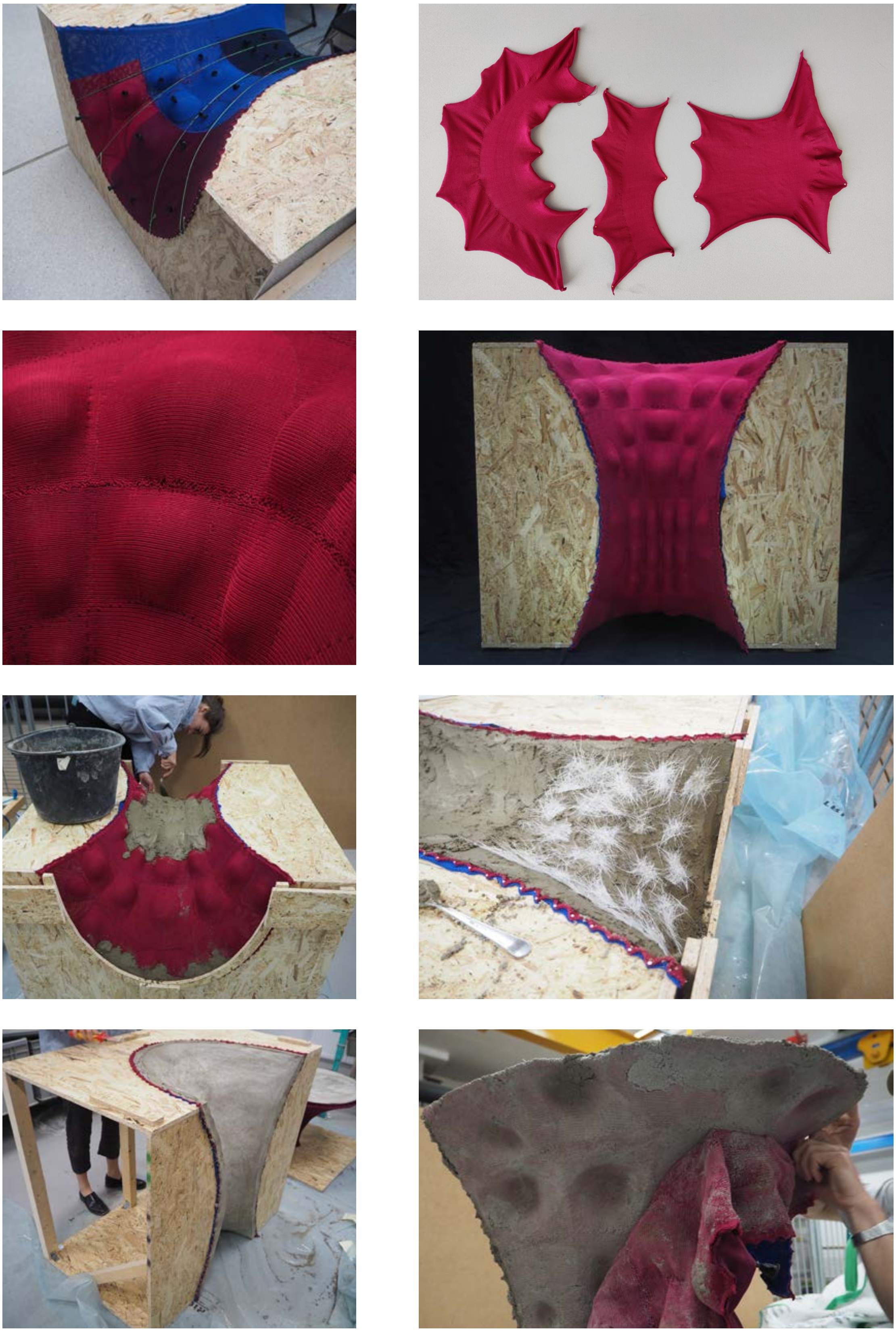


Figure 4.53 a. Mapping pockets b. Formwork before being sewn together c. Inflated pockets d. Tensioned formwork e. Coating of concrete f. Coating of second layer g. Finished cast before removing formwork h. Stripping of formwork

Figure 4.55 Finished model scale 1:5, side

Figure 4.55 Finished model scale 1:5, front

4.5.5. Design flow

Knitted formwork is a rather new production method making the design process also unknown. The proposed design process is to use a PPS simulation to do analysis in the conceptual development. The simulation is fast and gives a rather good simulation of how the fabric stretches and adopts its form during tensioning. An iteration where several input geometries can be evaluated fast much like seen in Figure 4.30. However, using the course knitting mesh gives a better result since the mesh density will be more accurate as appose to the general quadrilateral mesh used there. As seen in the model study would it be necessary to then in a later stage analyze the fabric with material properties etc to finalize the design. This process is of course more demanding and is therefore not appropriate in the conceptual phase of the work. The output deflected from the FE-analysis of the fabric can then be used for the analysis of the concrete shell. If there are issues regarding stiffness or buckling can the eigenmode parametrization be used as one strategy to find the placement of ribs.

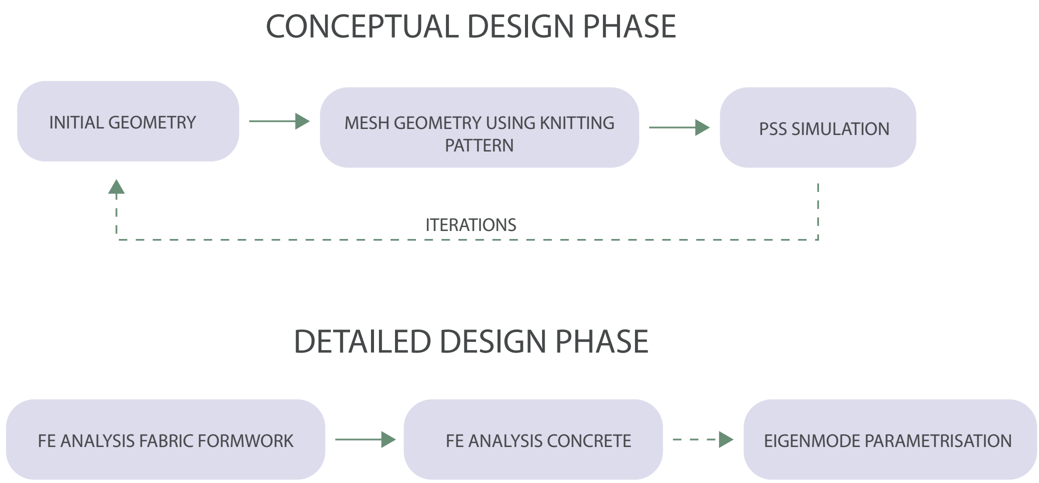


Figure 4.55 Workflow when designing shell structures using knitted formwork

4.5.6. FE-analysis

A linear elastic finite element analysis is performed for the umbrella structure. Concrete has a strong non-linear behavior since the material is prone to cracking in tension making non-linear material model a more appropriate for analyzing concrete. However, a non-linear analysis is a much more detailed and demanding analysis and the purpose here is to verify a high-level concept than rather do a detailed design. Furthermore, is the umbrella structure expected to be primarily in compression and therefore not subjected to cracking. The top slab is expected to be in tension, but the slab is not the main objective of the study. The slab would most likely be reinforced and to capture the interaction between the rebar and the cracking of the concrete would again a non-linear material model be used. However, as the objective is rather to study the umbrella shell will a linear analysis be performed and to get an close to accurate behavior will the slab have to restrain the edge to balloon out.

Since buckling is a prime concern of shell structures is also a buckling analysis preformed. Both the buckling and linear elastic analysis is performed in Rhino Grasshopper using the structural analysis plug-in Karamba3D. Since Rhino Grasshopper is used for the PSS as well is the geometry kept in one space making the iterations easy when modifying the geometry.

The geometry used as input for the analysis has been generated through a PPS simulation. The height of the structure is 4.5m and has a span of 12m. Based on the equilibrium state of the PPS model is a surface geometry generated. A rib geometry is generated consisting of 10 radial ribs and 5 circular ribs to connect the slab and the umbrella, where the slab seals the ribs on the top.

Loading

The structure is analyzed both in Ulitmate Limit State, ULS and Serviceability Limit State, SLS. The load considered is the crowd load for office space and as well as the self-weight of the shell. No horizontal loads have been considered as the horizontal loads will be transferred to the surrounding buildings.

Crowdload, q: 3kN/m2 (EN 1991-1-1:2002)
Self-weight, g: Calculated in software, density of concrete 25kN/m3

ULS combination: $1.35 \times g + 1.5 \times q$ (1)
SLS combination: $1 \times g + 1 \times q$ (2)

Material

The material properties for the analysis is taken from the paper for the KnitCandela project. (Popescu, et al. 2021) These properties are reasonable to use since the project is relatively similar to the project in this thesis. Both use knitted formwork and are shell structures. In addition, is the workability of the concrete of similar desires. The concrete is also fiber reinforced which is desirable for the otherwise unreinforced shell structure as this will function as crack control.

The concrete used in KnitCandela is the quite low quality of 20MPa in compression. By using this low-quality concrete is a point made that if the structure is designed to work efficiently and therefore there is no need to have high compression strength concrete that is more expensive.

Table 4.3 Material and element properties

Material	Design [MPa]
fck	20
ftck	4
Element	**Thickness [mm]**
Umbrella	40
Ribs	60
Slab	60

Result: linear elastic analysis, ULS

The stress plot for the principal stresses can be seen in Figure 4.58. The overall behavior is as expected. The slab is in tension and the majority of the umbrella shell in compression. However, there is some tension in the umbrella shell. As can be seen in the stress plot is the principle stresses do not exceed the material capacity. However, some areas are subjected to compression in one of the principal directions and tension in the other. To ensure that even these areas are within the failure envelope is the plane stress failure surface according to Mohr–Coulomb theory plotted. The principal stresses in each mesh face are plotted with the x-axis as the principal stress in the first direction and the y-axis the principal direction in the second direction. The principal stresses are plotted for both the top and bottom

Figure 4.57 Mesh used for FE-analysis

of the shell to capture the extreme values. As can be seen in Figure 4.50 are all the values within the failure envelope and the structure is therefore considered to be safe. The analysis shows that even the top slab has small enough stresses to withstand the tensile stresses with only fiber reinforcement. This is of course only symmetric loads and not taking into account creep etc. However, this indicates that the stresses are rather small as a result of the curvature.

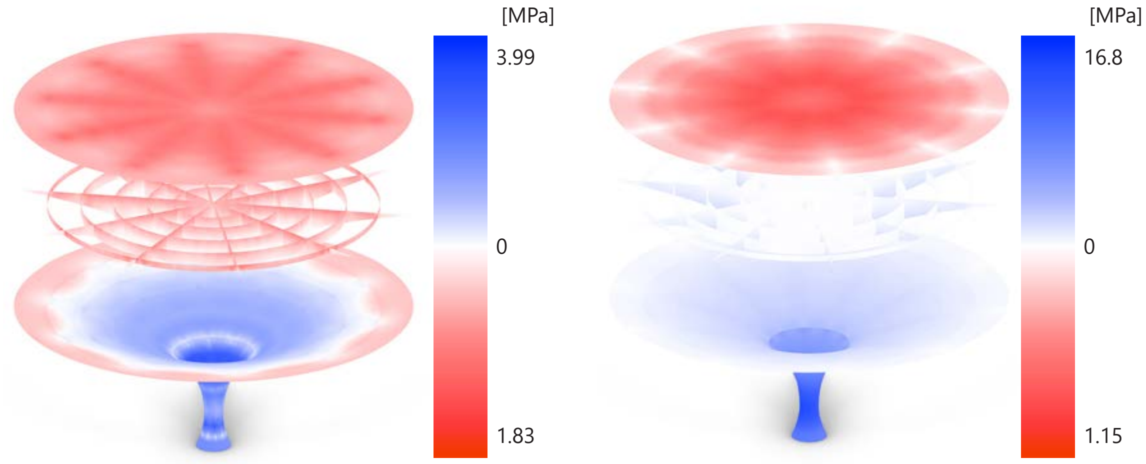


Figure 4.58 Stress plot for FE-analysis under ULS load combination with uniform load for the middle of the shell element

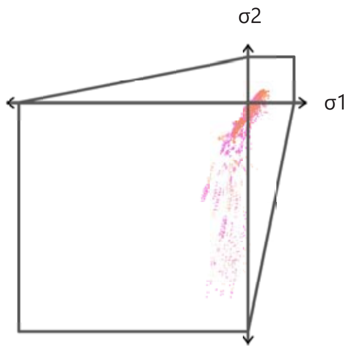


Figure 4.59 Mohr–Coulomb failure surface, purple plot for top of shell and red for bottom of shell.

Result: linear elastic analysis SLS
Deflection: 3.29 mm

The deflection of a concrete structure is very approximate using linear elastic analysis when the tensile stresses are above the tensile capacity of the concrete. Since the analysis shows that the stresses are below, making the result much more reliable. The deflection should be limited to span/250 (EN 1992-1-1, Cl 7.4.1). Which is fulfilled regardless is the span is considered to be 6 or 12m.

Result: buckling analysis
Buckling factor: 18.05 (under ULS load combination)

As the buckling factor is high and therefore no risk for buckling. As seen in Figure 4.61 is the first buckling mode effecting the trunk. This is because the top par has ribs connecting the slab and the umbrella shell. In addition to transferring the load from the slab to the shell do they also stiffen the shell from buckling.

To evaluate the influence of ribs placed for by the eigenmodes is a similar model used using only the umbrella shell. The umbrella is constraining in the top to x and y displacement to simulate the slab. The mass is redistributed according to vibration eigenmode maps. The first 100 eigenmode patterns are used for the sample pool.

The result is plotted in a diagram with deflection is represented on the x-axis and the buckling factor for the first mode on the y-axis. Some of the values from the pareto front are presented in Table 4.4 and compared to the homogenous thick shell. As can be seen, can the result be increased for both the buckling factor and the deflection. However, an improvement for the buckling factor does not inherently decrease the deflection and vice versa. Using for example vibration eigenmode 21 to redistribute the mass will improve the result for both stiffness and buckling resistance however the improvement is slight, approximately 1% for both. If only one of the two were to be optimized an improvement of 5-8% could be achieved.

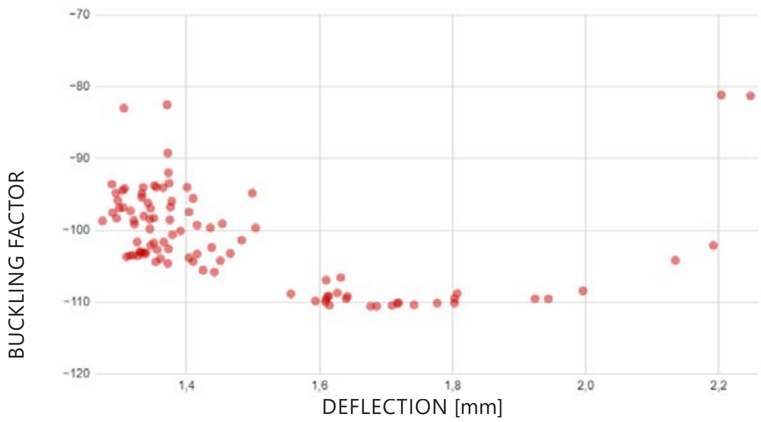


Figure 4.60 Buckling factor/deflection for massditribution based om 100 first virbation eigenmode patterns

Table 4.4 Buckling factor and deflection for different massditribution based om virbation eigenmode patterns

Pattern	-	22	78	87
BL	102.11	103.7	98.75	110.61
Deflection	0.1339	0.131	0.1274	0.1677

HOMOGENEOUS THICKNESS

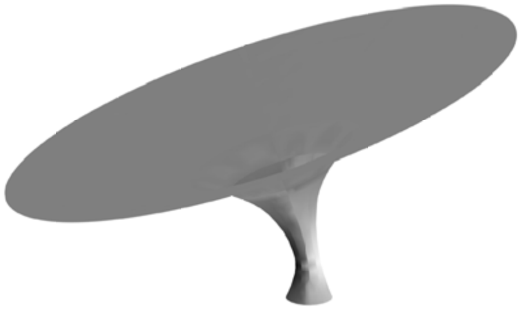


Figure 4.61 First buckling mode

Figure 4.62 Vibration eigenmode pattern 22, 78 and 89

4.5.7. Comparison to flat slab

To evaluate the material efficiency of the umbrella structure is it compared to a flat slab. The total volume of concrete for the equivalent floor area is compared. The thickness of the slab is determined using typical span to depth ratios. For a flat slab spanning 12m the depth is approximately L/30-L/40 (Schodel, 2004). To make a conservative comparison is L/40 used. In Table 4.5 is the areas and respective volumes presented.

Table 4.5 Area and volume of umbrella structure and flat slab

	Floor	Ribs	Umbrella	Total volume [m3]
Area [m2]	112.4	100.6	122	15.6
Thickness [mm]	60	60	40	
Area [m2]	112.4	-	-	33.7
Thickness [mm]	300	-	-	

As can be seen, is the umbrella structure approximately 50% less material than a regular flat slab. This comparison does not take into account the vertical support for the slab. Colum or wall elements would add more volume to the conventional floor system making it even more unfavorable.

4.5.8. Reflection of final design

The umbrella structure gives freedom in the arrangement in the plan as seen in Figure 4.43. A playfulness in the architectural expression can be achieved with varying the size and placement of the units. A secondary system is needed to span between the units however, a raised secondary floor system is not unusual even for "regular" flat slab structures as it is used to route technical systems.

The physical model study is conducted both to show the potential of knitted formwork as well as highlight issues. For the umbrella model, a new method of tensioning was used. Although it benefited in the ways it intended to, for instance avoiding pierce the fabric, it also had some drawbacks. As the size of the total knit is relies on the exact measurements of a single loop is it difficult to get accurate. In this case, the knit ended up slightly larger than intended. Since the rope was significantly stiffer was its length based on the expected circumference for the knit when fully tensioned. As a consequence, when the tensioning took place was the rope stretched to its limit however was the somewhat to large knit not tensioned properly. In the next iteration could a slightly more flexible rope that's closer to the stiffness of the knit be used. Thus, avoiding the rope becoming a rigid limit for the tensioning. The entire falsework frame was lifted 3cm, seen in Figure 4.50, to increase the stiffness somewhat. However, the result is a slightly more bulky-looking structure than intended. The curvature also reviles that the tensioning was too little since it changes sign. The fabric is, therefore, more "hanging" than stretched.

In the next iteration could a slightly more flexible rope be used. If the rope stiffness and knit stiffness were closer to each other would the rope have some more flexibility and not work as a rigid limit for the tensioning.

It also becomes obvious that an analysis of the fabric during casting would be necessary. As the material parameters are not known in this case was this not possible. However, if the parameters were known a pre-tensioning force could be calculated to ensure the stiffness of the formwork was sufficient to carry the load of the wet concrete.

The rib model showed next to no deformation during casting. This formwork was easier to tension properly since this was done by pulling on the fabric directly. This model also had continuous support both top and bottom as well as along the sides. In this model, the formwork was removed and therefore the concrete surfaces could be examined. Some lines on the concrete can be seen. When coating the formwork the knit flexed from the point load casing the rather dry concrete to fracture. This could be a result of the lacking practical experience in casting concrete possessed by me and August who produced the models. It could also be an indication that the surface must be stiffer or the point load eliminated. The stiffness of the surface could be increased by increasing the pretension. The tactic adopted in KnitCandela was to spray the surface with cement coating before coating the concrete to have a stiffer surface to work on. The concrete could also be sprayed on to have a more spread load in contrast to the point load of a trowel.

The FE-analysis of the shell structure show promising result as the stresses are relativity low. In further iterations could different arrangement of the rib structure be evaluated to maximize the stiffness gained at the same time minimize the volume of the concrete. In addition should non-symmetrical loads be introduced to evaluate if the any tensile force will be introduced in the umbrella shell where it's difficult to place rebar reinforcement.

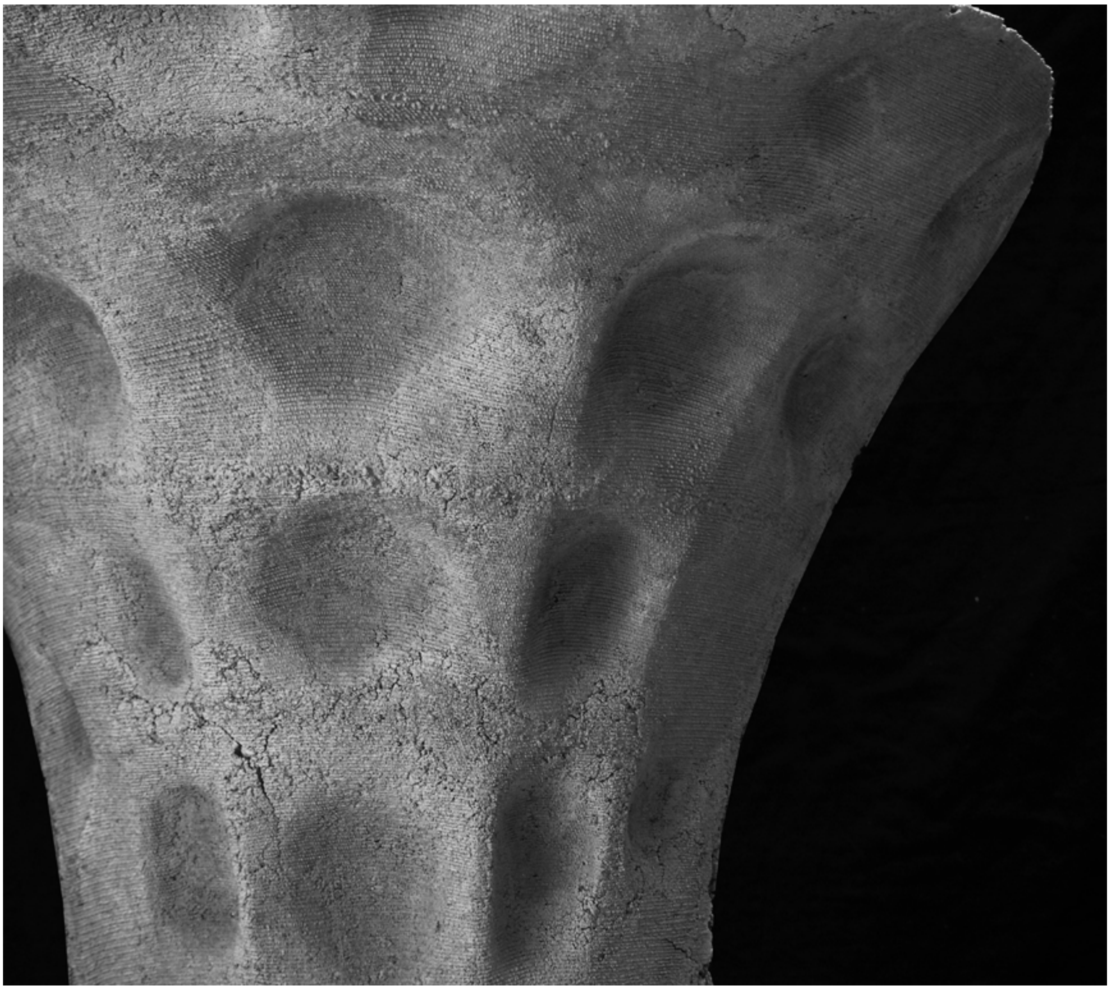


Figure 4.63 Close-up of model scale 1:5

5. Discussion

In this chapter will the findings in this thesis be interpreted and described. The discussion will cover the major parts of the thesis starting with the method implemented in the thesis moving on to the constraints and benefits of knitted formwork and relating that to the context of other production methods. Attempting to concretize the potential of knitted formwork and highlight areas that need further research.

Method

The method used in the thesis is a research-by-design approach with a focus on exploration through models. This was quite natural since there is limited research done in the field and a lot of the conclusions had to be based on observations during modelmaking. The iterative process allowed for the work to start at the most basic level with small cloth samples, working towards bigger models. Going to a larger scale was crucial as different aspects could be studied. For instance, was the erection sequence for the umbrella structure somewhat confirmed. But it also showed the sensitivity for the shape and size of the formwork.

As the design study was put in a real context were there more demands to consider. This made the thesis somewhat scattered but also in some ways more relevant. For instance, are shell structures rarely designed to have a flat slab in order to create several stories. But as the overwhelming majority of new building consists of more than one stories is this where optimized structural systems can make the most impact when reducing material.

Geometrical restraints of knitted formwork

The knitted formwork has both its limitations and possibilities. For instance, is the anticlastic curvature necessary to pretension the formwork, which is a very evident restraint. However, the umbrella structures do not have the shape of a true minimal surface that is often used in membrane structures. A PSS with zero-length springs will only provide surface that looks similar to a minimal surface but is in fact not. This could be the reason for the slight wrinkling where the trunk starts its expansion in the umbrella structure. The structure of the knit with the linked loops allows for some deviation without wrinkling as the yarn can be somewhat redistributed. A woven fabric would most likely shown much more wrinkles.

If a true minimal surface would have been used would the tensioning of the fabric not alter the geometry as much making it easier to predict. However, this would further limit the design space. This forces the designer to take a stance, if it’s tolerated to deviate from the “pure” solution, in this case a true minimal surface, to gain some freedom in the design. Same question can relate to shell structure where the purest shell is the pure compression shell with razor sharp edges. The realization of the imperfect reality can be very harsh if no room for freedom is allowed. However, the cost of the divergence should be made known, making it a conscious choice and not out of ignorance.

Figure 5.1 Speculative visualizations

Figure 5.2 Speculative visulazations with columns with eigenmode patterns

Cost comparison
Factoring the production method into the design can have significant impact on the overall cost of a project. This becomes very evident when comparing the two very similar arena structures of Seattle kingdom and Montreal stadium. The cost per seat was more than doubled for the Montreal Olympic stadium compared to the Seattle Kingdom as the Kingdom was from an early stage designed with the construction method in mind. (Billington, 1990)

According to Candela was his hyper umbrella shells the cheapest and simplest thing in the world to make, producing 280 000 m2 in 4 years' time. The straight timber formwork meant a significant reduction in labor intensity for the formwork. (Campbell, 1959) However, since then has the cost of labor significantly increased, between 8-11 times between 1958-2007 for the US market. The cost for material has not increased as much making labor more costly than material. (Veenendaal, 2017)

A timber formed shell costs in today's market 400-800 euro/m^2. As knitted formwork is relatively new is there not much data relating the cost of such formwork. If compared to membrane roof structures, that is the most similar examples as it is also a tensile structure, is the cost approximately 300 euro/m^2. (Veenendaal, 2017) Since the cost for a custom the formwork for a concrete shell can represent as much as 70% of the cost (Popescu, 2019) can a conclusion that tensile membranes could be cost competitive to regular formwork. The KnitCandela project that was produced using knitted formwork cost 575 euro/m^2 (Popescu, et al. 2021) however, was that only a small sculpture and prices tend to go down when the scale of the project goes up. At the same time as this was a university driven project making it not ideal to use as a cost example. Although it can still give an indication, affirming that knitted formwork could potentially not only reduce waste but also the cost. In doing so increasing the feasibility of project with complex, bespoke, double-curved geometries.

Eigenmode patterns
Using vibration eigenmode patterns does have its advantages. Any surface can quickly be parametrized providing endless amounts of patterns to choose from. The patterns themselves are arguably visually appealing as they subtly relate to the surface. If a pattern would instead be superimposed the distortion and/or kinks would not provide the same coherence with the global geometry.

The large-scale model, as well as speculative renders of shell structures where the eigenmode patterns have been used to redistributed the mass, are also convincing of the visual appeal. The gentle curvature in contrast to the raw concrete gives a very unique expression.

However, the structural implementation of these patterns is still in need of further research. Although some evidence of increased stiffness or buckling resistance is presented in the thesis is there still not enough material to give a more holistic understanding. A discussion of what kind of vibration mode to use is still unanswered. Is a higher mode preferable since it breaks up the geometry from the lower buckling modes? Or is the lower buckling mode preferred since the node lines will be stiffened attracting load away from the sensitive areas? Or as in this thesis, can the patterns be used to aimlessly plot the result and choose from the best performing.

Comparison to other formwork
The comparison to other formwork alternatives is difficult since each formwork imposes its unique benefits and constraints. The unique benefits of knitted formwork include the lightness of the formwork, which makes it easy to transport even to remote locations. The geometry can also easily be customized without increasing the cost and work as a stay-in-place formwork covering the interior with fabric that can be used decoratively or as an acoustical damper. It also imposes a natural curvature to the structure that can be used to benefit the structural system reducing the volume of concrete. Maybe above all is the fabrication close to waste-free making it a more sustainable way to create curved geometry within architecture.

However, knitted formwork can by no means be considered a universal solution. Learning from Nervi and Candela is to acknowledge that engineers need to be aware of the holistic view. Not only design the finished structure but to let the finished structure reflect the fabrication method. The structure can not be a true expression of efficiency if not both parts are taken into consideration.

> I should have to so design buildings that they would not only be appropriate to materials but design them so the machine that would have to make them could make them surpassingly well.
>
> *- Frank Lloyd Wright, 1932*

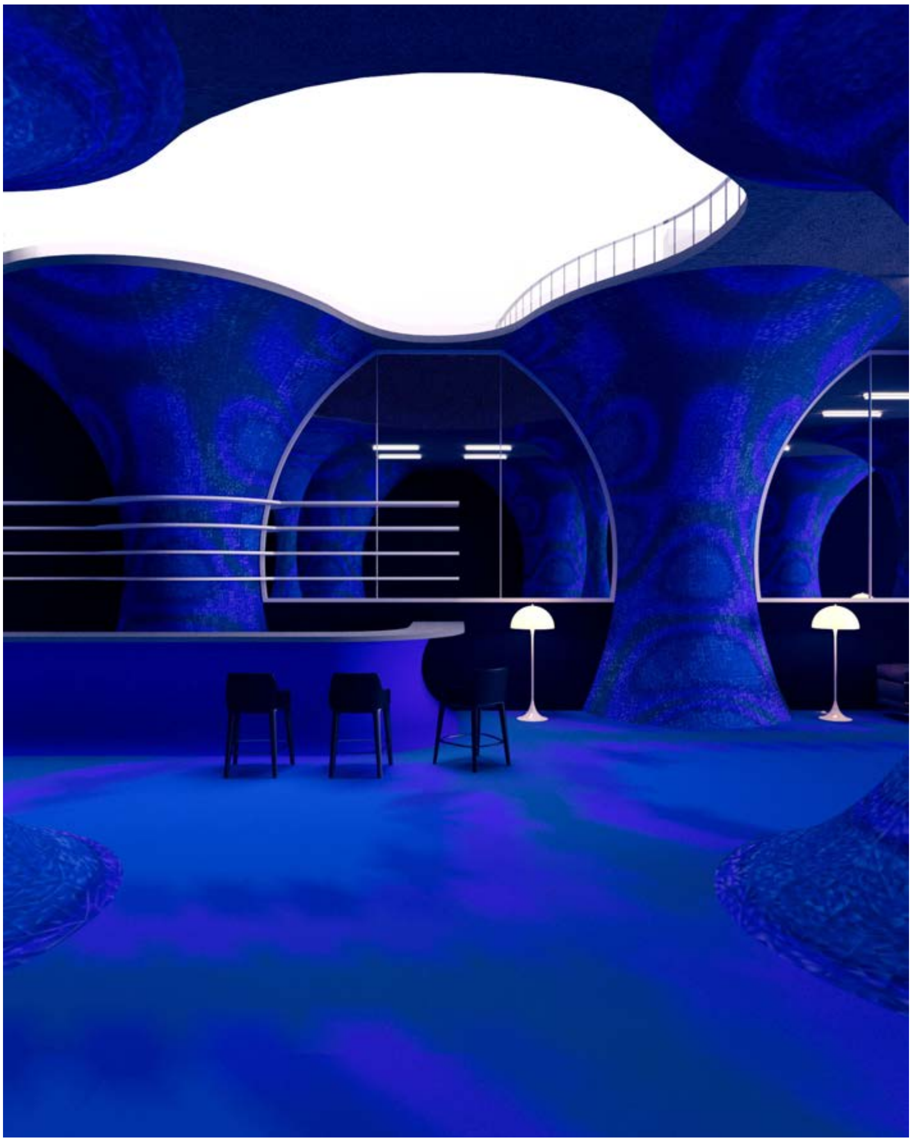


Figure 5.3 Speculative visualizations of with the knitted formwork as a part of the interior design

6. Conclusion and future work

The thesis aimed at exploring the field of knitted formwork in a context of a design study. This was done both through physical model making and computational simulation. Many material samples were produced to reflect on the quality of the knit and how the knit could be modified through different knitting techniques.

The collected knowledge from the model study is later applied to a structural element that was evaluated in a preliminary design phase. The element shows some of the possibilities in the combination of knitted formwork with shell structures. Not only significantly reducing the waste and cost of the formwork, but also reducing the volume of concrete.

Even though the potential of knitted formwork is vast and much yet to be explored, it also imposes many limitations on geometry. Knitted formwork should therefore not be seen as the single solution to concrete casting but one way of creating curved structures without extensive, costly, or wasteful formwork.

Lots of interesting future work is to be done in the area of knitted formwork. What was not conducted as a part of this thesis is a detailed analysis of the formwork during pre-tensioning and casting. To do so material parameters are needed, such as Young's- modulus, poisons ratio, etc. These sort of parameters are available for other membranes but very much lacking for knitted fabric as the implementation on an architectural level has been very limited. Therefore would a thorough examination of the material knitted fabrics be of much interest moving forward. Material behavior such as creep is also of interest if this could affect the quality of the cast.

In this thesis is the knit pre-tensioned to create a surface which is coated with a thin layer of concrete. Future exploration of the creation of more solid elements would be interesting. Instead of pre-tensioning the fabric to minimize deflection during casting taking advantage of it and use this to shape the final element. Using different knitting techniques to alter the relative deflection to shape the concrete.

As the thesis emphasis model building, a natural next step is to go up in scale in future work. Even doing tests on a full architectural scale. KnitCandela is certainly a great example, but further additions to the built references would develop a deeper understanding and validate the fabrication method further.

BIBLIOGRAPHY

Adriaenssens, S., Block, P., Veenendaal, D., & Williams, C. (2014) *Shell structures for architecture: Form finding and optimization.* ISBN 9780415840590

Bechthold, M. (2008) *Innovative Surface Structures: Technology and Applications,* ISBN 9780415419673

Block, P. (2020) *Strength through Geometry* [Video]. YouTube. youtube.com/watch?v=a4NJCuJ1geg&t=3205s

Billington, D. (1990) *Thin shell concrete structures: Second edition,* ISBN 00700052794

Campbell, B. (1959) *Nervi's contribution to the new Rome: buildings for the 1960 Olympics. Concrete Quartaly*, July-September , Volume 42

Chilton, J. (2010) *Heinz Isler's Infinite Spectrum: Form-Finding in Design*. https://doi.org/10.1002/ad.1108

Cirio, G., Lopez-Moreno J., and Otaduy M. A. (2017) *Yarn-Level Cloth Simulation with Sliding Persistent Contacts*, IEEE Transactions on Visualization and Computer Graphics, vol. 23, no. 2, pp. 1152-1162, 1 doi: 10.1109/TVCG.2016.2592908.

Gallery 400. (1958) *Los Manantiales Restaurant* [Fotografi] Creative commons. https://search.creativecommons.org/photos/2e78bc7f-c65d-44cb-9c6d-d18ab463ffe9

Gallery 400. (1958) *Production of los Manantiales Restaurant* [Fotografi] Creative commons. https://search.creativecommons.org/photos/1ea0fcce-51c5-478e-9558-4f1012bdd284

Hörteborn, E. (2020) *Textile architecture informed by wind* [Licenciatavhandling, Chalmers tekniska högskola]

Nervi, P. (1956) *Structures,* ISBN 100070462704

Nervi, P. (1965) *Aesthetics and technology in building* ISBN 9780674007017

Olsson, J. (2020) *In conversation with simulation: The application of numerical simulation to the design of structural nodal connections* [Licenciatavhandling, Chalmers tekniska högskola]

Omer A. (2018) *75.9 construction process, Surrey* [Fotografi] https://omerarbel.com/projects/75-0/

Popescu, M. (2019) *KnitCrete, Stay-in-place knitted formworks for complex concrete structures* [Doktorsavhandling, ETH Zurich]

Schodel, D. L. (2004) *Structure, Fifth Edition.* ISBN 0130488798

Popescu M., Rippmann M., Liew A., Reiter L., Flatt J. R., Van Mele T., Block P. (2021) S*tructural design, digital fabrication and construction of the cable-net and knitted formwork of the KnitCandela concrete shell, Structures*, Volume 31, Pages 1287-1299, ISSN 2352-0124

Veenendaal, D. (2017) *Design and form-finding of flexibley formed concrete shell structures* [Doktorsavhandling, ETH Zurich]

Veenendaal, D., & Block, P. (2014) *Design process for prototype concrete shells using a hybrid cable-net and fabric formwork.* Engineering Structures, 75, 39-50.

Watts, J. (2019) *Concrete: the most destructive material on Earth.* The Guardian. URL https://www.theguardian.com/cities/2019/feb/25/concrete-the-most-destructive-material-on-earth

West, M. (2016) *The Fabric Formwork Book: Methods for Building New Architectural and Structural Forms in Concrete,* ISBN 0415748860