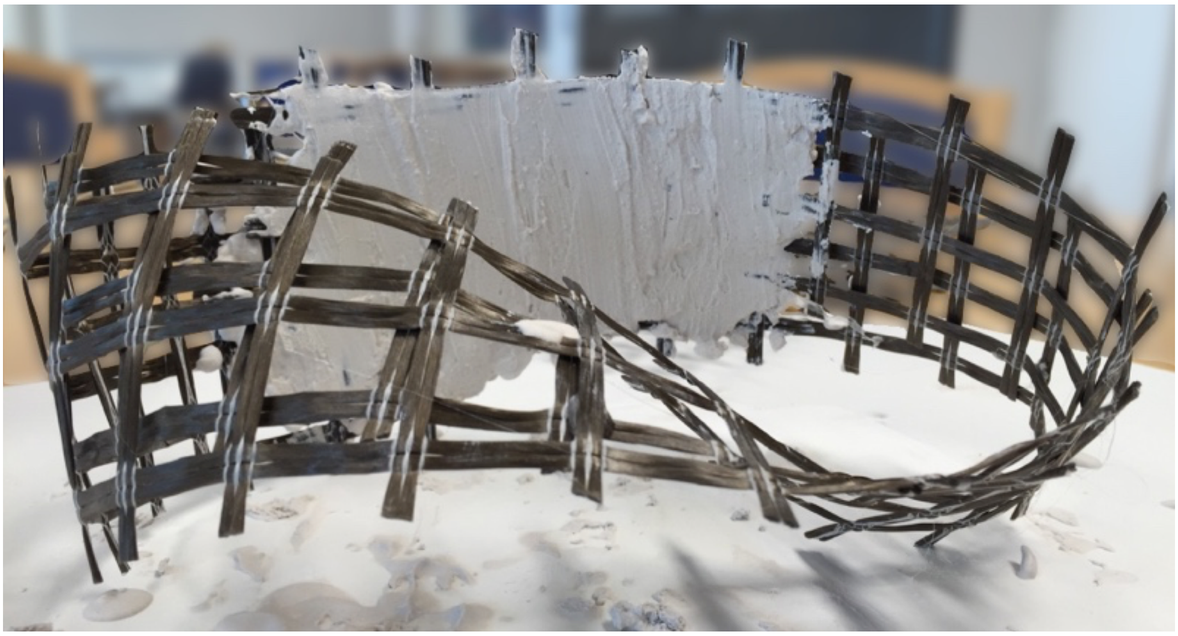

Complex shapes with textile reinforced concrete

An investigation of structural form, material and manufacturing

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

ELLEN SIMONSSON

Department of Architecture and Civil Engineering
Division of Structural Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY

Master's Thesis BOMX02-17-97
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Cover:
Conceptual model for a complex shaped textile reinforced structure. (Photo: Ellen Simonsson)

Department of Architecture and Civil Engineering Göteborg, Sweden 2017

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ABSTRACT

Concrete with steel reinforcement is the most common construction material used today, but due to the high risk of corrosion which can lead to demolished structures new reinforcement materials have been requested. Promising material textile made of glass, carbon or basalt fibres. With this reinforcement the structure can be both thinner and more sustainable.

There are few existing structures with textile reinforced concrete, and most of them are 2-dimensional elements such as rectangular façade elements. It is believed that more complex concrete structures can be created with this type of reinforcement, but more investigation of the reinforcement, design and manufacturing method are needed.

The purpose of this thesis was to explore different design methods, shapes and production techniques for textile reinforced concrete, with the aim to highlight new types of concrete structures which should fulfil the concept; *thin, formable and strong*.

Theoretical and practical work was conducted parallel to get a better understanding of the material and physical and computational models where developed in an iterative process.

During the process, different design and manufacturing methods were stated and with this investigation some methods and shapes showed to be more promising than others.

Finally, the plan was to make a mechanical bending test on one structure, but due to difficulties and time limits this could not be done.

Even though there were some difficulties with the manufacturing it was concluded from this investigation that complex structures with curved, thin and sharp edges can be made with textile reinforced concrete. With developed and better tools in the manufacturing process the results in the thesis indicates that both investigated design methods and the material open up for more innovative concrete structures.

Key words: textile reinforcement, concrete, design, structural design, manufacturing, design process, physics modelling, parametric modelling

Komplexa Former med Textilarmerad Betong
Undersökning av strukturell form, material och tillverkning
Examensarbete inom Konstruktion
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SAMMANFATTNING

Betong med stålarmering är det vanligaste konstruktionsmaterial som används idag men på grund av den höga risken för korrosion, vilket kan leda till förstörda konstruktioner, har nya armeringsmaterial efterfrågats. Forskning har visat att ett lovande material är textil tillverkad av glas-, kol- eller basalt fibrer. Med denna typ av armering behövs inte lika mycket betong vilket är positivt för både miljö och ekonomi.

Det finns några befintliga konstruktioner av textilarmerad betong, och de flesta av dem är 2-dimensionella element såsom rektangulära fasadelement. Det är troligt att andra och mer komplexa betongkonstruktioner kan skapas med denna typ av armering, men mer undersökning av armeringen, design och tillverkningsmetod behövs göras.

Syftet med detta arbete var att undersöka olika designmetoder, designkoncept och tillverkningsmetoder för textilarmerad betong och att lyfta fram nya typer av betongkonstruktioner med komplexa former.

Teoretiskt och praktiskt arbete utfördes parallellt för att få en bättre förståelse av materialet och både fysiska- och beräkningsmodeller utvecklades i en iterativ process.

Under arbetet har olika design och tillverkningsmetoder undersökts och några metoder och former visade sig vara mer lovande än andra.

Slutligen skulle ett mekaniskt test göras på en konstruktion, men på grund av svårigheter med tillverkningen och tidsbrist kunde detta inte genomföras.

Även om det fanns svårigheter med tillverkning drogs slutsatsen från denna undersökning att komplexa strukturer med böjda, tunna och skarpa kanter kan göras med textil armerad betong. Med mer utvecklade och bättre verktyg samt förståelse för tillverkningsprocessen visar detta arbete att olika designmetoder och textil som armering öppnar upp för mer innovativa betongkonstruktioner.

Nyckelord: textilarmering, betong, design, konstruktionsteknik, tillverkning, design process, fysik modellering, parametrisk modellering

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Preface

The intersection between structure, material and design has been a growing interest for me during my studies. In this thesis project I took the chance to work with this interest to develop my own knowledge but also to investigate a new field in a theoretical and practical way. By being inspired of Martin Westerling and Patrik Thorsson and their master thesis about textile reinforced concrete in 2015, and Filip Nilenius' work at Chalmers University of Technology, I got this idea of exploring my interest with textile reinforced concrete.

During spring 2016 this master thesis of 30 credits was carried out. The work has taken place at Chalmers University of Technology at the Department of Structural Engineering and Building Physics.

First and foremost, I would like to thank my supervisor and examiner Filip Nilenius, for constant feedback, help and support during my whole work, from idea to final conclusion. I am also grateful to Martin Westerling for rewarding discussions and Sebastian Almfeldt and Marek Machowisk for support during the manufacturing. I would also give extra thanks to my opponent Johanna Riad, which has given me advise and support constantly through my work.

Göteborg 2016-08 ELLEN SIMONSSON

1 Introduction

1.1 Background

Steel reinforced concrete has many advantages and is the most common building material today due to high load bearing capacity, economical efficient, and several manufacturing and design possibilities (Domone & Illston 2010). However, a big disadvantage is the risk of corrosion. Corrosion of the steel bars lead to reduction of the load bearing capacity and many structures have been destroyed and demolished due to this. Therefore, it is desirable to find new reinforcement solution that can be used instead of steel, which does not have the same risk for corrosion. Textile reinforcement is one of them.

Textile reinforced concrete is a relatively new material on the market, and has many advantages (Brameshuber, 2006). The structures can be thinner when there is no need of an extra protective layer of concrete, hence the cement consumption can be reduced and with that also cost and weight of the structure. Due to less material, and especially cement, which emit large amount of carbon dioxide in their manufacturing, the impact on the environment is reduced for textile reinforced concrete compare to steel reinforced concrete (Williams Portal, 2013).

Research of the material indicates possibilities in variations of form and design. It is believed that textile reinforced concrete will open up a new field of applications of sustainable and innovative engineering and architecture with concrete. This is a desirable property when more architects design buildings with irregular curved shapes, as for example the architecture firm Zaha Hadid Architecture which has for mention some designed London aquatics centre for the Olympic games and Heydar aliyev centre in Baku.

Few constructions of textile reinforced concrete exists today, and most of them are roof, façade or other rectangular structural elements. To widen the applications, experimental models of textile reinforced concrete have to be developed and investigated to get a better understanding of load-bearing capacity, form, production and the relation between them. From this kind of research, new rules and concepts can be applied for structures in the future (Brameshuber, 2006).

1.2 Purpose and objectives

The main purpose was to investigate how the material can be used in complex forms and also in which ways.

In order to explore structural form and the materials possibilities this thesis focuses on textile reinforced concrete in more complex structures, i.e. structures with curves, sharp edges, holes etc.

The objectives of this thesis were to:

- Investigate structural behaviour of complex forms with textile reinforced concrete.
- Investigate suitable forms and different ways to design structures with textile reinforced concrete.
- Investigate appropriate manufacturing techniques.

1.3 Aim

The aim of this thesis was to find suitable structures for textile reinforced concrete which should be structural efficient, aesthetical and should fit into the concept *thin, strong and interesting shape,* three adjectives that indicates the material's properties well. The structures should have a form and design that suits the material's properties and preferable a design that should be complicated to design with steel reinforced concrete to indicate the material's use. The structure should also highlight textile reinforced concrete's performance as a structural and architectural component.

1.4 Limitations

One of the main purpose of the thesis was to investigate the material's properties in complex structures. The design process, structural performance and aesthetic were the main subjects and economy was not a factor which was included. For the same reason, the calculation and tests of the structure was mainly focus on global stresses. Bonding between the concrete and the textile was not tested.

The structure should be able to be manufactured and mechanically tested in Chalmers' concrete lab, which limitation the size of the casted structures and test methods. The manufacturing was done by two persons which limits the production methods.

The function of the structure, which was decided from the most promising forms, has to be in a smaller scale, i.e. structures as furniture or a smaller pavilion, such that it is possible to cast a reliable model.

The main focus during manufacturing was technique, reinforcement and form. There was no investigation in different concrete compositions.

1.5 Method

To investigate the objectives and the purpose, it was chosen to work iterative both in theory and practice. The main purpose was divided into

- Structural
- Form
- Manufacturing

which were analysed in different ways.

In order to get a better knowledge of the subject, a literature study was conducted as a starting phase. This study contained

- The material's structural behaviour (concrete and textile)
- Existing projects
- Different manufacturing and design methods

With this literature study as an initial foundation, the investigation continued by designing of physical models in smaller scale. The physical models where evaluated and three models were chosen to be developed further into computational models.

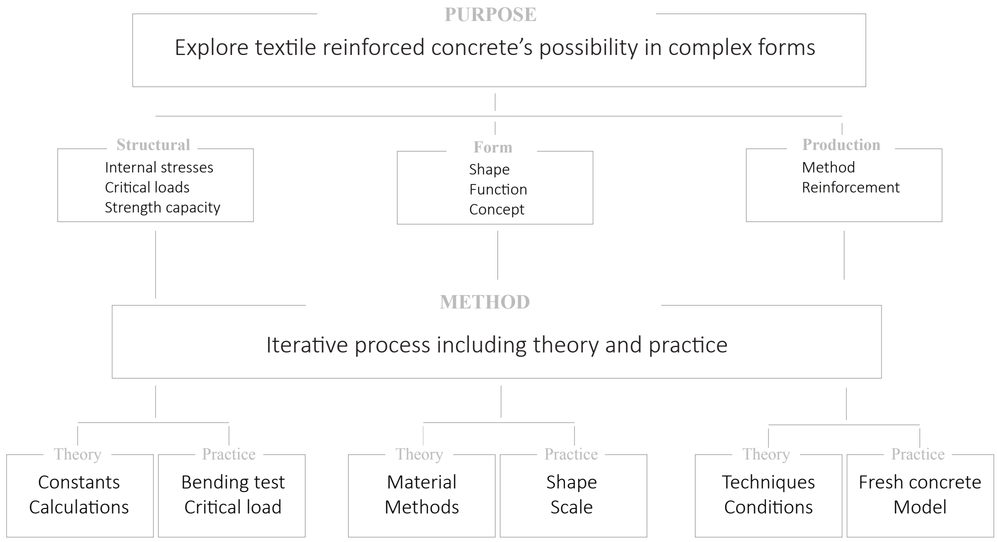
The software used;

- 3D-modelling program Rhinoceros
- Plug-in paramedic program Grasshopper
- FE-analyse program Karamba

After the computational analyses the models were manufactured with different techniques. A second evaluation was conducted to choose one model to manufacture in full scale which also was tested with mechanical load to examine crack load, failure load and location of the first crack. This was done to investigate the capacity of the material in a more complex form and also to compare the computational FE-model with the physical model. The result of the tests was mainly addressed in practical demonstration and work.

To investigate and get knowledge of possibilities, ability and disadvantages of the material's designs and functions, the physical models were equally important as the computational models, and had close relation to each other. This resulted in a working process where the integration between architectural form and engineering solution was highly important and needed to be considered during the whole process.

Below, a scheme illustrates the relation between purpose and the chosen method.



2 Textile Reinforced Concrete

In this chapter it is described the fundamentals of textile as reinforcement, the concrete properties and how textile and concrete work together.

2.1 History

Concrete has been used for building construction since the Roman Empire and was an important material for significant buildings and infrastructure during this period. With the fall of the Roman Empire, the knowledge of concrete was lost, and therefore most of the buildings before the 17th century are made of brick, stone or timber.

Architects and structural engineers begun to build with concrete again in the 17th century when the architect Vitruvius writings describing fundamentals of concrete structures and production from 25 B.C. were found in a monastery in Switzerland. The renaissance of concrete was also influenced by the industrial revolution with new manufacturing techniques which lead to an easier and efficient production (Redlund, 2008).

The material has been improved in many aspects. Even though it is said that the Romans built with the first concrete, the material used today has different behaviours and can be used in other applications (Shaeffer, 1992).

Concrete has a high compression strength and is therefore a good material choice for compressed structures such as vaults and shells. One example is Pantheon's dome constructed in the second century A.D with a span of 43 meters in diameter (AleckAssociates, 2016), creating an unique architectural space. In the mid 19th century engineers and technicians all over the world started to reinforce concrete with steel bars to increase the material's bearing capacity in tension, and during 1871-75 the first reinforced concrete building was constructed in Port Chester, NY. (Shaeffer, 1992).

2.2 New reinforcement

Due to the high risk of corrosion, the reinforcement needs to be protected and therefore it is often covered with an extra layer of concrete. Even so, corrosion attacks have still demolished and destroyed structures long before estimated service life time.

Therefore, two alternatives for reinforcement with no risk of corrosion have been investigated the last decades; fibre and textile reinforcement.

In Fibre Reinforced Concrete, (FRC), the fibres are mixed into the fresh concrete mixture and are randomly distributed in the structure. The fibre reinforcement's properties depend on material, orientations and distribution. Due to the fibres are mixed in the concrete, it is difficult to know and estimate the correct behaviour and capacity of the reinforcement.

Textile Reinforcement Concrete, (TRC), has reinforcement containing of long and continuous bounds of fibres which are weaved and oriented in a specific direction and order.

Compared with fibre reinforcement, textile reinforcement can be more efficiently used when it is possible to place it in the right direction and according to the main stresses in the structure (Kok, 2013). The different reinforcement types are shown in Figure 2-1.

Since both alternatives have no risk of corrosion the structure need less concrete, which is both more environmental sustainable and cost efficient. The behaviour and properties of the materials that are known today indicates that both reinforcement can be used in greater scales and open up for new types of concrete structures. The reinforcement alternatives are relatively new and thus not commonly used in practice. Hence, all the long term effects are not known. Corrosion is not a problem, but other problems with these types of reinforcement might be revealed in the future.

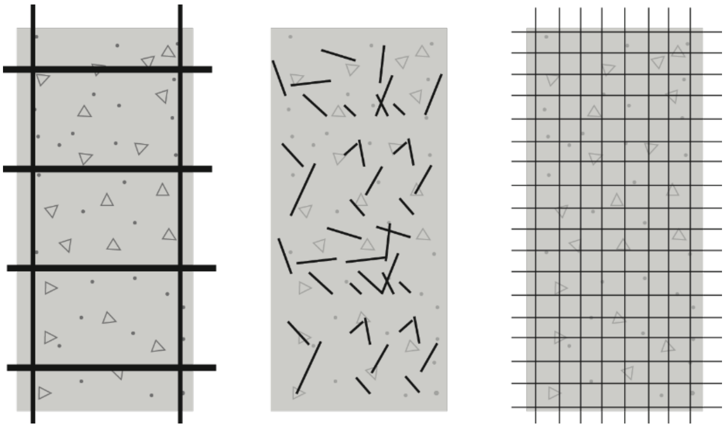


Figure 2-1. Illustration showing different types of reinforcement for concrete. From left; steel bars reinforcement, fibre reinforcement and textile reinforcement. (Illustration: Ellen Simonsson)

2.3 Textile

Textile reinforcement is a net of yarns which can be manufactured in various designs and shapes. The yarns contains of either filaments or staples, see Figure 2-2.

Staple is the name of a fibre which has a limited length. A common natural staple is cotton.

Filament is the name of fibres with continuous length, and can exist in nature but also as man-made fibre.

Yarn is a continuous strand of filaments or staples which are grouped together. This can be done in several ways depending on the future use and method of fabrication. Most common is to place all filaments in the yarn parallel and drawn (Mahadevan, 2009).

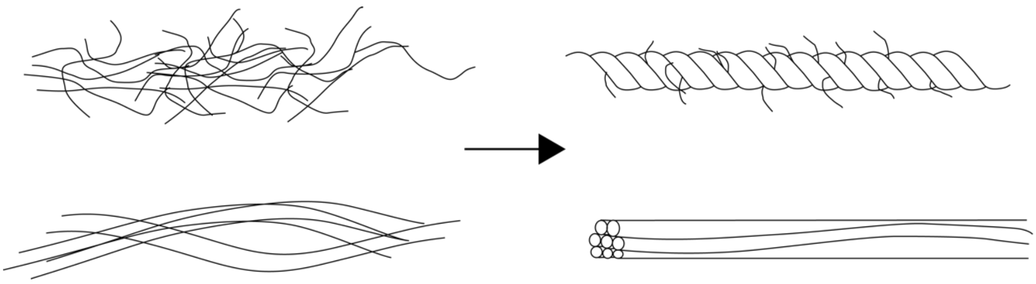


Figure 2-2. To left, staples and filament. To right yarns containing of staples respective filaments. (Illustration: Ellen Simonsson)

The yarns are either knitted, woven, non-woven, glued or plaited together (Peled et al., 2008). The most common textiles are bi- or multi-axial warp knits where the yarns run sideways in the fabric. There exists several different types of yarns and textile with different properties and behaviour, but the main importance for the design of textiles are to ensure a good permeability and a complete envelopment with the concrete. The textiles shall therefore have a high displacement stability and an open structure (Brameshuber, 2006). To obtain a certain property for the textile there are several techniques how to organize the filaments or staples (Fall, 2014). In order to have a suitable reinforcement for different kind of application, the design of the textile can vary in more or less open structures and in shape. In figure Figure 2-3 and Figure 2-4, 2D and 3D reinforcement are shown.

Figure 2-3. 2D reinforcement. (Photo: Ellen Simonsson)

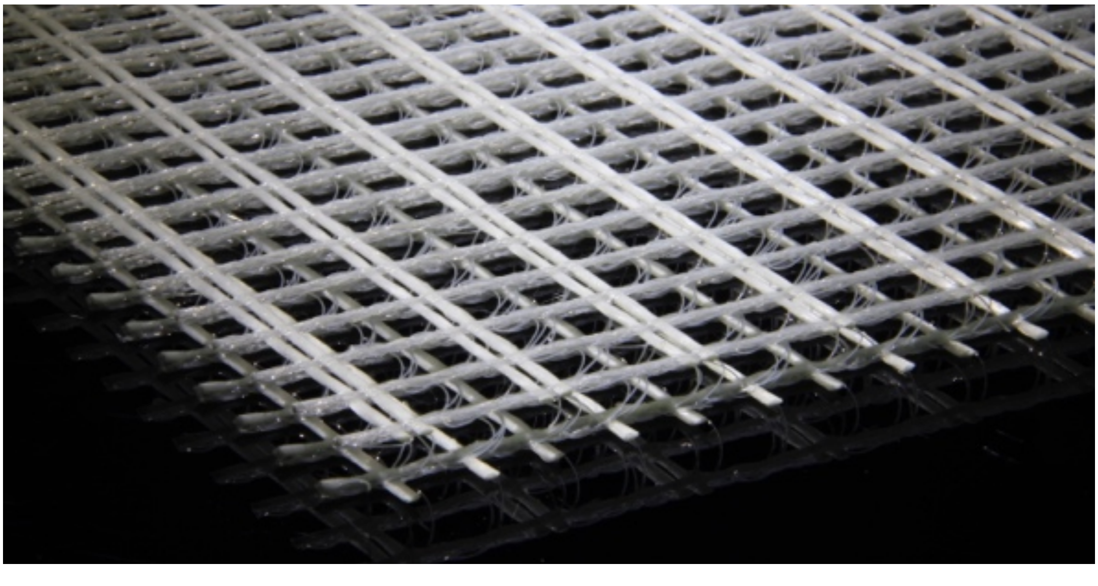


Figure 2-4. 3D reinforcement. (Photo: V.Fraas Solutions in Textile)

For bi-axial textiles the yarns are placed in two directions; 0 degrees, called warp and 90 degrees called weft, see Figure 2-5. The yarns can be described by two parameters; the wave length and the wave amplitude (Williams Portal, 2013). Due to the fixed direction of the yarns, the strength in a certain direction can be estimated which is not possible for fibre reinforcement. By placing the reinforcement in the same direction as the main tensile stress, the textile strength will be optimally used (Scholzen et al., 2015).

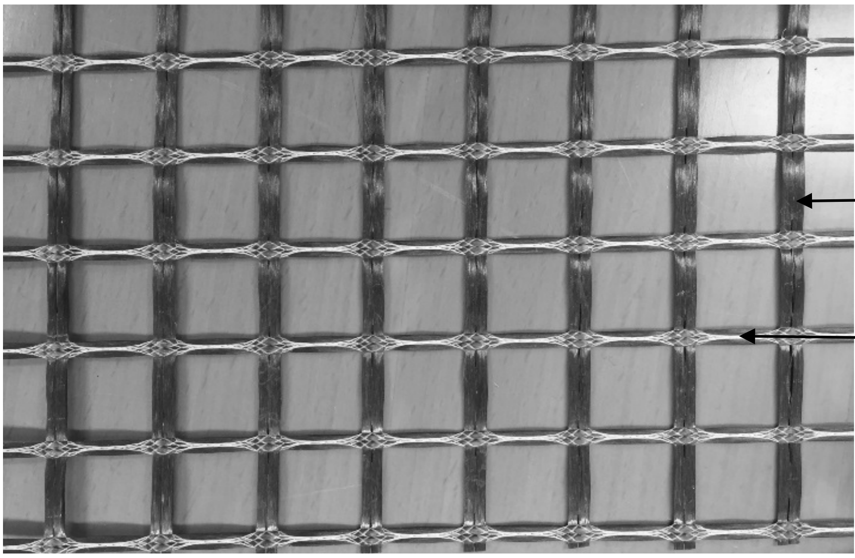


Figure 2-5. Warp and weft direction. (Photo: Ellen Simonsson)

2.3.1 Textile Material

Suitable fibres material for textile reinforcement shall have several essential properties:

- Good tensile strength
- High breaking elongation
- Higher elasticity of modulus than the modulus for the concrete

The reason for the third is due to, even though cracks occur in the concrete, the stiffness of the structure should not be reduced. There are several materials which have these properties as AR-glass, carbon, basalt and aramid to mention some.

The properties of textile reinforcement varies depending on material, amount of reinforcement and the arrangement of the fibres (Brameshuber, 2006).

Carbon fibre

Carbon is a synthetic polymer. Cellulose was the main material in carbon fibre until the 1960's when it changed to polyacrylnitrile, (PAN). Carbon fibres have a high tensile strength, god vibration reduction, low heat expansion and small creeping. Today, carbon fibre is common in automobiles and sports goods, but is also believed to be a suitable material as reinforcement in concrete.

Disadvantages with carbon fibre as reinforcement is the cost and the not so good adhesion properties. Compared to basalt and AR-glass, the adhesion ability is low (Williams Portal, 2013). The adhesion properties can be improved by designing special sizes of the filaments in the yarn and by coatings, but further research is needed before it can be used commercially. (Brameshuber, 2006).

Basalt fibre

Basalt fibres are manufactured from basalt rock through a melting process. The cost is low due to the manufacturing process and the availability. Basalt has a good tensile strength, a greater failure strength than carbon fibres and a good resistance to chemical attack. Basalt also has a high resistance to fire (Sim et al., 2005).

It has been investigated how basalt fibres reacts with the alkali environment in concrete by immersing the material in a sodium hydroxide solution. It has been shown that the volume of the fibres reduces after time and also the tensile strength. This is due to the fact that silicon dioxide (SiO_2) in the basalt fibres reacts with the alkali solution. AR-glass fibres have the same problem, and a nano-composite polymer coating has been developed to protect the AR-glass against alkali ions (Williams Portal, 2013). This could also be a solution for basalt fibres to improve its durability. Research of structural behaviour and chemical properties implies that basalt fibre is a suitable material as reinforcement in building structure even though the strength capacity is less compared with carbon and glass fibres (Sim et al., 2005).

Alkali-resistant (AR) glass

AR-glass fibre mainly contains a melted mixture of silica sand, clay and limestone. Two main advantages of using AR-glass fibre as reinforcement are the good adhesion ability and the cost efficiency. As mentioned the fibres react with the alkali ions in the concrete, which lead to a volume reduction, hence less strength capacity. This reaction can be reduced with coating and specific concrete mixture with less alkali ions content

In Table 2.1reinforcement properties for carbon- basalt and AR-glass fibres and steel reinforcement B500B are presented.

Table 2.1. Structural and chemical properties for different types of reinforcement

Reinforcement material	Density [g/cm^3]	Tensile strength [GPa]	E-modulus [GPa]	Elongation failure [%]	Adhesion ability
Carbon fibres	1.8[1]	2-4.5[1]	200-250[1]	1.7[2]	**Low to average** Weaker adhesion if the filament diameter is smaller, this can be improved by coatings.[4]
Basalt fibres	2.7[3]	1.9[4]	90-100[2,3]	3.15[2]	**Average** It has a low friction coefficient but can be improved by coatings.[4]
AR-glass fibres	2.8[1]	1.4[1]	70-80[1]	2[1]	**Average** Depending on the density, and chemical attacks, but can be improved with coatings.[4]
Steel (B500B)		0.5[5]	200[6]	2.5	**Low to high** Depending on mechanical deformations and surfaces.[4]

2.4 Concrete

As always when designing concrete, it has to be designed for special demands and requirements regarding use and manufacturing process. For TRC, the demands differ compared to ordinary steel reinforced concrete in some cases. The maximum aggregate has to be chosen dependent on the size of the open structure of the reinforcement due to penetration ability. It is commonly said that the size should not be greater than 2 mm (Williams Portal, 2013). This leads to an increased amount of cement paste which gives a higher impact of the energy consumption. This could be solved if a good penetration and enclosure of the reinforcement can be ensured even though greater size of aggregates are used (Pettersson & Thorsson, 2014).

[1] (Brameshuber, 2006)
[2] (Kok, 2013)
[3] (Dhand et al. 2014)
[4] (Williams Portal, 2013)
[5] (W.Salvatore, S.Caprili, A.Braconi, M.Finetto, L.Bianco, C.Ascanio, J.Moersch, C.Apostolopoulos, 2014)
[6] (Al-Emrani.M, Engström.B, Johansson.M, 2011)

The fresh concrete needs to have a suitable consistency for full penetration of the textile to get a good adhesion. It should also be workable in the production process. The hardened concrete must be durable and fulfil all load bearing demands.

The textile and concrete need to work together to achieve a sustainable and durable composition. Therefore, the main aspect is to get a full penetration between the textile and the concrete in order to guarantee a good bonding and load bearing behaviour. Hence, the consistency of the fresh concrete has to be designed with regards to the textile's material and mesh. In general, it is highly recommended to use fresh concrete which is highly fluid in order to penetrate the textiles.

The composition also need to be considered in regards to the production process. When injection is used, highly fluid concrete is preferable, but for techniques like lamination or pultrusion, plastic consistencies are required (Brameshuber, 2006). When the TRC elements are produced with the latter techniques, a denser mesh of the textile can be used, which also could lead to advantages such as higher bearing strength (Kok, 2013). The production techniques are described in Chapter 3.

As mentioned in 2.3.1basalt reacts with the alkali ions in concrete which leads to volume reduction of basalt, hence lower bond ability. This affect can be reduced by adding substances that lower the alkali ions content. Adding fly ash and silica fume are therefore recommended in the concrete mixture when basalt or AR-glass are used as reinforcement. By adding silica fume, the consistency will change and become more rigid, hence the content of silica fume is limited to 10% of the total mass of binder content (Brameshuber, 2006).

From tests which were performed by Björn Banholzer, Tanja Brockmann, and Wolfgang Brameshuber (Banholzer et al., 2006), several concrete mixtures have been investigated both for short and long term mechanical behaviour. The concrete mixtures which showed a good result, had a highly fluid consistence and a finer structure compared to ordinary concrete due to small aggregates size and to different pozzolanic additives. In Table 2.2 the composition mixture of PZ-0899-01, which was used for experimental investigation, is shown.

Table 2.2 Composition of the concrete mixture PZ-0899-01.

Cement (c)	490 kg/m^3
Fly ash (f)	175 kg/m^3
Silica fume (s)	35 kg/m^3
Water (w)	280 kg/m^3
w/b (w/(c+f+s))	0.4 [-]
Plasticiser	1% of binder
Siliceous fines (0-0.25 mm)	500 kg/m^3
Siliceous sand (0.2-0.6 mm)	714 kg/m^3

The characteristic mechanical behaviour of PZ-0899-01 is shown in Table 2.3.

Table 2.3. Characteristic mechanical behavior.

Young's modulus	Design value Compressive strength	Shear modulus	Poisson's ratio	Ultimate strain
E_{cm}	f_{cd}	G	v	ε_{cu}
N/mm^2	N/mm^2	N/mm^2	-	mm/m
32.000	57	13.223	0.21	5.5

Research has shown some disadvantages with fine-grained concrete. It shows a lower stiffness and higher shrinkage strains and stress strains, which need to be considered in the concrete mixture and if it is suitable for the planned application.

In Diagram 2.1, the stress-strain relation is shown for several types of the fine-grained concrete and ordinary concrete (C80).

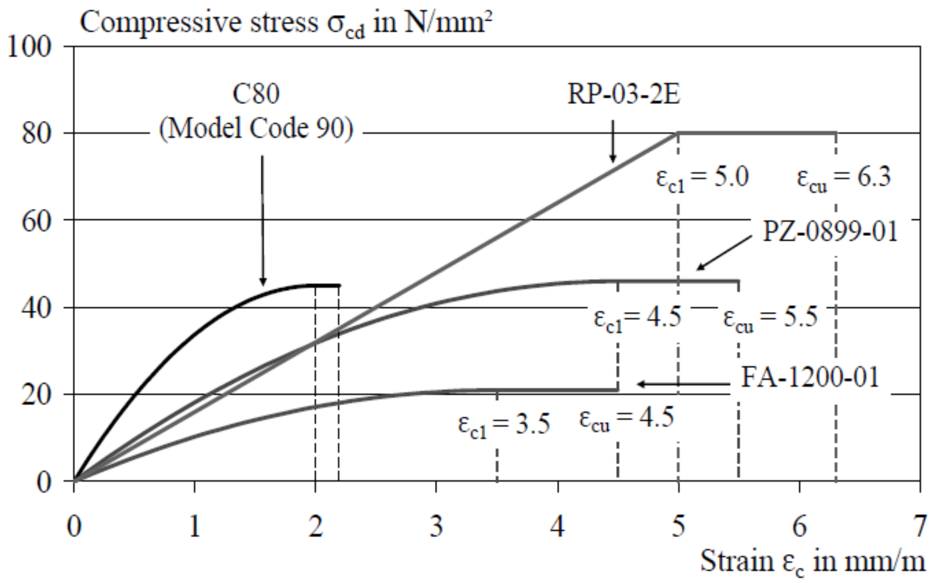


Diagram 2.1. Stress-strain relation for fine-grain concrete used in TRC and ordinary concrete C80 (Kok, 2013).

2.5 Interaction between reinforcement and concrete

TRC's load bearing capacity is dependent on four main contributions;

- the mechanical quality of the textile and concrete
- the interaction/bond between the textile and the concrete matrix
- the amount of fibre
- the orientation and fibre-layout

(Dhand et al., 2014).

When tests have been made under uniaxial loading, TRC shows the same behaviour as conventional reinforced concrete, with a similar stress-strain relation, with three different states, see Diagram 2.2.

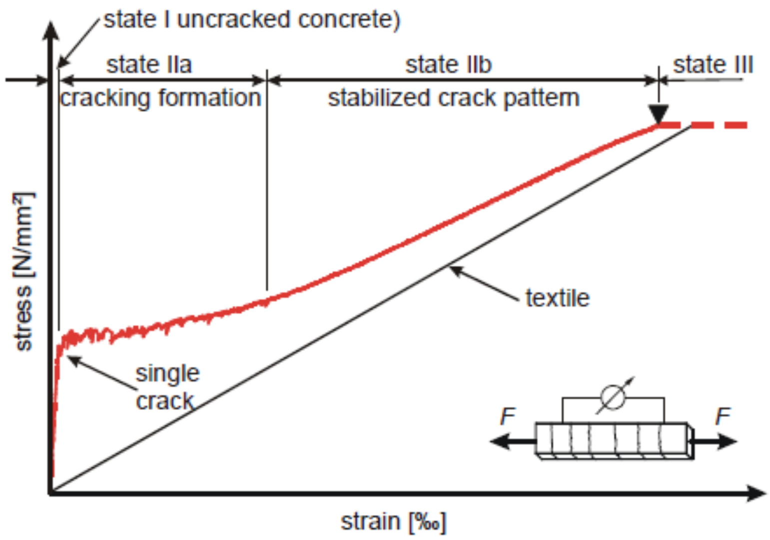


Diagram 2.2. Stress-strain relation for TRC is similar to ordinary concrete with three different states (Kok, 2013).

The mechanical behaviour for TRC cannot be derived only by knowing the reinforcement's and the concrete's qualities and properties. The interaction between the materials have to be considered as well.

What has been seen when comparing textile and textile casted into the concrete is that the tensile strength changes with an effective factor $k_1<1$.

$$k_1 = \frac{\sigma_{max}}{f_t}$$

where

σ_{max} = maximum tensile stress for TRC

f_t = tensile stress for textile

The effective factor for carbon reinforcement is 0,69 (Banholzer et al. 2006).

This reduction in strength is due to the bond qualities between the fibres and the concrete, but also due to the interaction between the filaments in the yarn.

Hence, although the strength is estimated for the material separately, it cannot be adopted to be the same for the finished composite material, thus it is needed to test the finished TRC structure (Brameshuber, 2006).

2.5.1 Bonding

As mentioned, the bonding ability is of main importance of the load bearing capacity of TRC and is investigated by a pull-out-test which gives a relation between bond stress/slip and pull-outload/displacement. From the first relation, a friction coefficient can be estimated, and from the second one the maximum pull-out load is found.

Tests made by Banholzer, Brockmann and Brameshuber with AR-glass reinforcement and the concrete matrix PZ-0899-01, shows that the bond stress is almost independent on the slip i.e. the friction bond between the filaments and the matrix is almost constant. Results also shows that the maximum pull-out load is approximately 500 N (Banholzer et al., 2006).

The pull-out load varies a lot for reinforcement made of basalt fibres and the explanation is not definitely known.

The failure mode for textile reinforcement is dependent on how the matrix envelop the yarns i.e. where the filament or staples are placed. The filaments or yarns which are placed in the core, does not have the same adhesion/bond with the concrete, and the maximum pull-out load is therefore less than for the outer filaments or yarns with direct contact with the concrete, see Figure 2-7 (Kok, 2013).

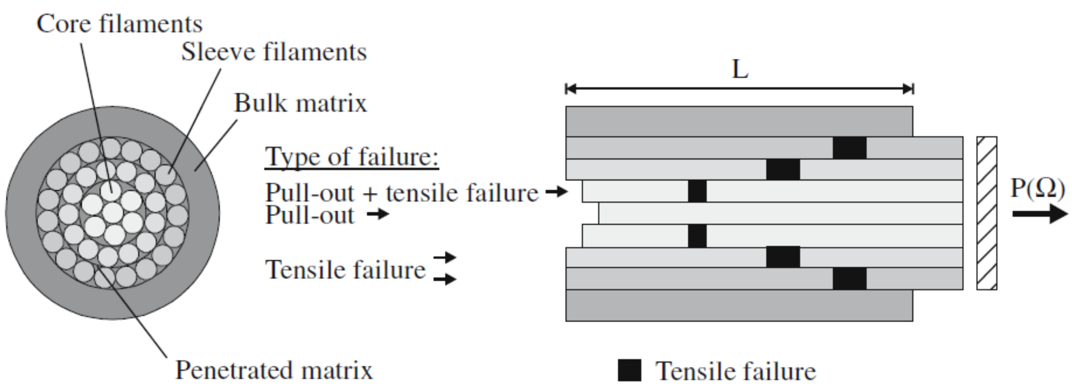


Figure 2-7. Failure mode for textile reinforcement (Kok, 2013).

3 Production methods

The behaviour of TRC structures mainly depends on the textile and the production method. Hence manufacturing process needs to be taken into consideration early in the design phase and be highlighted to utilize the design potential of the material (Schneider et al., 2006). There are several different methods used today and in this chapter some production techniques are presented.

3.1 Formwork

The most common materials used for formwork in industry are wood, plywood and steel. The formwork is of high importance for the finished structure, the behaviour, appearance and the total cost. In industry it is estimated that just the formwork accounts up to 55% of the total cost for the structure. The material choice of the formwork is important than the surface will be reflected to the concrete structure.

The formwork has to be entirely closed, in order to prevent fresh concrete leaking, and in most case the formwork has to be able to be removed when the concrete has hardened. There are cases for ordinary concrete, where a steel frame is used both as formwork during manufacturing and as reinforcement in the finished structure (Pallett, 2004).

To create rectangular elements of concrete, a simple formwork of wood can be made, but for more complex shapes other techniques have to be applied. Ongoing research in the field explore different possibilities of formwork and what these can bring into the architecture and structure, and also with economical and sustainable aspects. The ongoing research TailorCrete, which is founded by EU, combines several divisions to make experiments in small and big scales with an aim to contribute to new techniques of how to create efficient concrete structures with complex forms. The research includes digital architecture, new formwork and materials as well as digital robots fabrication tool (Tailor Crete).

At the *Centre of Architectural Structures and Technology* (C.A.S.T) at University of Manitoba, Canada, is an ongoing investigation of fabric as formworks. This investigation explores how to use geo-fabric as formwork in order to create more variations in forms. The method is based on physical actions and the casting procedure has become more of an artistic investigation in itself (West, 2011).

3.2 Manufacturing

The structures geometry and load bearing capacity is influenced by the manufacturing method. Some manufacturing methods exclude different forms and other the amount of reinforcement.

Casting

This method is commonly used, also for ordinary concrete. A formwork is made and the reinforcement is placed before the concrete is poured into the formwork. The formwork is later removed from the hardened structure, see Figure 3-1. The reinforcement can either be fixed or loose to the formwork. To ensure the placement or the reinforcement spacers are used. To ensure that the reinforcement is enclosed by the concrete it is preferable to use a fluid concrete as well as vibrations (Triantafillou, 2016).

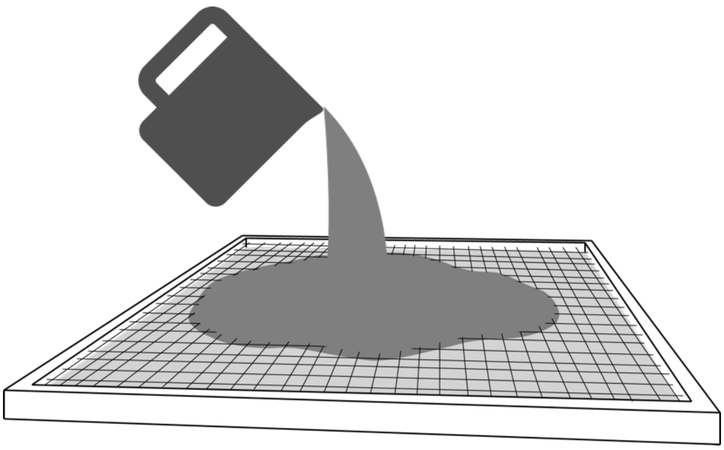


Figure 3-1. With a formwork with fixed or loose reinforcement the concrete is casted. (Illustration: Ellen Simonsson)

Laminating (Hand lay-up)

The laminating method, also called hand lay-up, is one of the oldest manufacturing methods which is simple and therefore also the most common techniques for fibre reinforced composites. The method is used for different structures and functions as for car bodies and aircraft wings.

The procedure is divided into four steps.

1. Form work preparation
2. Gel coating
3. Laminating
4. Finishing

The finished structure will have the same visual appearance as the formwork, hence the surface and the material of formwork is of main importance, and to ensure a smooth surface a gel coating is often applied on the mould (Brameshuber, 2006). The matrix is spread evenly in the form work and the reinforcement is placed over it. To ensure contact between matrix and reinforcement a roller is used. This is repeated until required amount of reinforcement and thickness are obtained, see Figure 3-2. The concrete can be highly fluid and rather stiff, both have shown good bonding with reinforcement. A very similar method is to use shotcreting where the procedure looks the same, but the concrete is sprayed instead of applied. This is preferable to use when more curved surfaces are made (Triantafillou, 2016).

The advantages with this method lies in its simplicity and the possibility to create large structures with a complex form. But it is time consuming and also the meticulous hand work need highly skilled workers (Brameshuber, 2006).

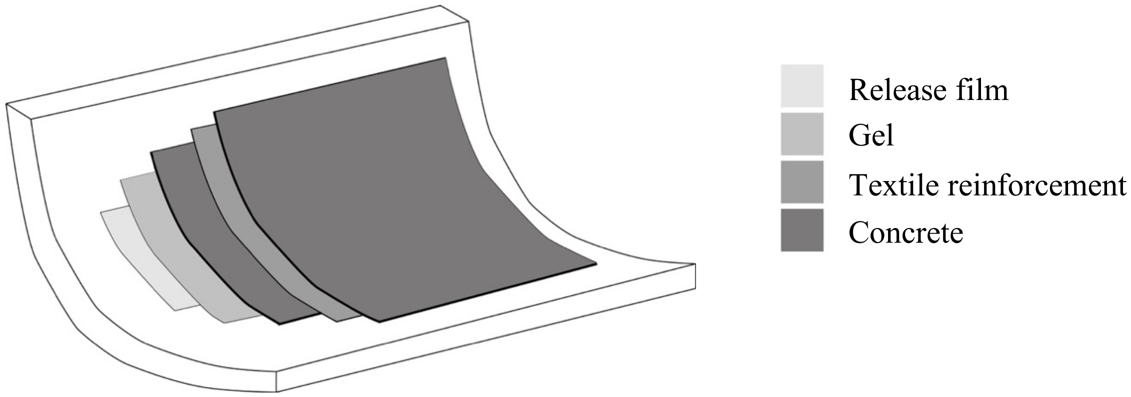


Figure 3-2. Illustration showing the different layers in hand lay-up method.(Illustration: Ellen Simonsson)

Pultrusion

With the pultrusion method it is possible to produce sheets with various length, thickness and width without a formwork. In this production method the textile is pushed through a slurry infiltration chamber, see Figure 3-3, and further through several squeezed rollers. In the slurry infiltration chamber the textile is enveloped by concrete matrix, which in the rollers are squeezed in the openings of the textile. The concrete matrix has high requirements regarding consistence using this method. It has to be fluid enough for the textile to transfer through the matrix in the slurry infiltration chamber, but still dense enough to remain on the textile when leaving the chamber. (Brameshuber)

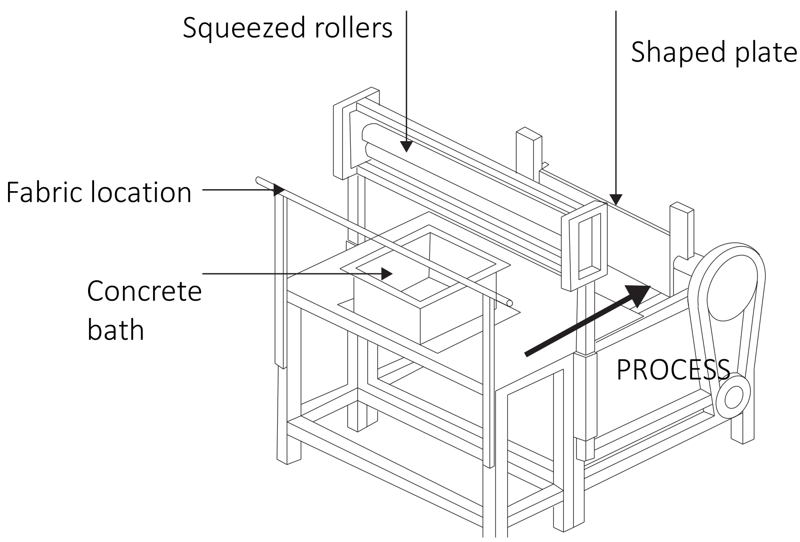


Figure 3-3. Putrusion process. (Illustration: Ellen Simonsson)

3.3 Spacer

Due to the components properties, the risk of displacement of the reinforcement is high and to reach the aimed capacity of the material it is important that reinforcement is fixed in the right place. This can be done with appropriate spacers. One example is shown in Figure 3-4 (Schätzke & Schneider, 2006).

Figure 3-4. A spacer can be added at the reinforcement to guarantee right place and distance. This one is from DistTEX (Photo: DistTEX)

4 Applications

The possible applications for TRC open up for new and innovative design freedom for architects and engineers. It has been shown from investigations that TRC has unique behaviour and properties that can contribute to both structural engineering and architecture (Brameshuber, 2006). With further investigation regarding load bearing capacity, production methods and forms suited for the material, new ranges of applications and appearance are possible for concrete structures (Hegger et al., 2007).

4.1 Existing structures

TRC is not common. There are still questions that need to be solved in regards to durability, bonding and loadbearing capacity.
TRC has been used successfully as a retrofitting system for already existing conventional concrete structures with steel reinforcement and in the last several years it has been used for new structures as well. Several of these projects are designed by RWTH Aachen and Dresden University in Germany which are at the forefront of research in TRC. There are also companies, which have a strong believe in TRC, which have been built very slender bridges in the material.

4.1.1 Roof Structure

Figure 4-1. Pavilion at Aachen University made of a roof structure of TRC.(Photo: Bauko 2, RWTH Aachen University) (Scholzen et al., 2015).

Textile reinforced pavilion

Location:	Aachen University
Application:	Seminar and event pavilion

At RWTH Aachen University a roof structure was designed for a seminar and event pavilion and is planned to have glass walls on all sides. The pavilion consists of a roof structure of TRC and streel reinforced concrete columns. The roof is made of four thin TRC elements which are double curved as hyperbolic paraboloids and refers to the structural design and projects of Felix Candela which worked during mid 20th century. Felix Candela designed several slender roof structures, but due to the high risk of corrosion and the complex in situ formwork this kind of design of concrete is not common today with ordinary reinforcement. But with TRC, structures like this are both sustainable and durable.

The TRC elements are 7m x7m in plan and the thickness varies from 6 cm at the end to 31 cm in the middle over the column to ensure a capacity such that load can be transferred from the roof to the column (Scholzen et al., 2015).

4.1.2 Bridge

Figure 4-2. A 100-meter-long pedestrian bridge in TRC, is today the longest bridge built in TRC. (Photo: InnovationsinTextiles 2011)

TRC Pedestrian Bridge

Location:	Albstadt
Application:	Pedestrian bridge
Construction year:	2010

In co-operation with Aaschen University, the contractor Groz-Beckert built a pedestrian bride of TRC in 2010 in Albstadt, Germany. The bridge is approximately 100 meter which is the longest bridge made of TRC in the world.

At the same place, a concrete bridge had to be demolished due to corrosion problem after just 30 years, and it was requested that the new bridge should guarantee a service life of 80 years. Another requirement was that the bridge should be slender. From these requirements the proposal of a TRC-bridge won and was built in one year. Textile reinforcement made of AR-glass was used, which was formed as a grid inside the bridge's construction. Due to this design, the height-to-length ratio is 1:35, and the appearance of the bridge is very slender (InnovationsinTextiles, 2011).

4.1.3 Façade elements

TRC Façade elements

Location: Aachen

Application: Curtain façade wall

Figure 4-3. Façade elements of TRC.

The new extension building of Institute of Structural Concrete at RWTH Aachen University has a façade made of textile reinforced concrete. The elements work as cladding. With a thin construction of just 25 mm (compared to regular concrete elements that should be 70-100 mm) the cost and weight were reduced. Due to reduction of weight the need of complex anchors was also eliminated.

For this type of design, a more common material is natural stone. Using TRC the manufacturing became easier and the cost was reduced.

Coated AR-glass fibre is reinforcement, and the concrete layer (from the reinforcement to the concrete edge) is 4 mm. A fine-grained concrete was used and due to this, the surface became smooth with sharp-edged profiles (Brameshuber, 2006).

5 Design Techniques

Different methods and techniques can be used for design structures and architecture. Depending on context, material and form, different techniques are more suitable than others. *Form-finding*, *simple mathematical geometry* and *free form* are three different techniques which Mangelsdorf (2010), explains further in the Journal *Architectural Design.* Form-finding is based on physical constrains defined by internal and external forces. The simple mathematical geometry method is when a complex surface or design is explained by parametric of simple geometry or mathematical formulas. Free form method are independent of the two previous and the design has no physical constrains and no foundation in geometry or mathematic (Mangelsdorf, 2010).

5.1 Models

In product design and in architecture, models are common in the design process. Models both answer and raise questions of the structure that can be difficult to see without a model, and therefore it plays an important role in the design process. A model provides important insights of shape, material, behaviour and construction, which often are difficult to gain from other sources. Models can often be divided into two fields; physical models and digital models. Both have pros and cons, but in the end communicate and give information about the design and construction (Stoll, 1999).

5.1.1 Physical Models

Salwa Isa discuss model making in the design process in the article *Classifying Physical Models and Prototypes in the Design Process* (Isa, 2001). Isa refer to other studies and investigations which all have different, but positive views and believes that physical modelling during the design process playing an important role.
The possibilities to see the shape in 3D in different angles gives new perceptions and the model address opportunities and identify problems. It also allows the designer to experiment with material, context and shape.
To work with physical models early in the design process gives the designer an understanding of construction and the final manufacturing procedure which often leads to a better and more economical and efficient product. In the article it is also stated that different types of models are preferable to use in different states in the process in order to address concept, production and function. The model also works well as a communication tool (Isa, 2001) in all stages of the design process. Isa, refers mostly to the working process for a product designer but also in the structural engineering and architecture field this way of working has been successful which can be seen in the works of Frei Otto.

Frei Otto (1926-2015) was an educated architect but also worked as an engineer. He won the Pritzker Prize in 2015 and have worked with many projects as for example the Olympic stadium in Munich. He had a strong belief in physical models in the design process due to its three dimensional appearances. He meant that working with three dimensional models, the structure becomes more real where forces could be understood in the space, and not just in a two-dimensional plane. (Dezeen Magazine, 2015). He observed and analysed how the forms generated themselves during the

form-finding process in physical models to find an aesthetic but also an efficiency structure (Otto & Rasch, 1995).
Some of the methods and material which Frei Otto worked with are described below.

Soap film
The method with soap film played an important role in Frei Otto's work developing design and construction for tension loaded structures than the soap film creates a natural form from external and internal forces, see Figure 5-1.

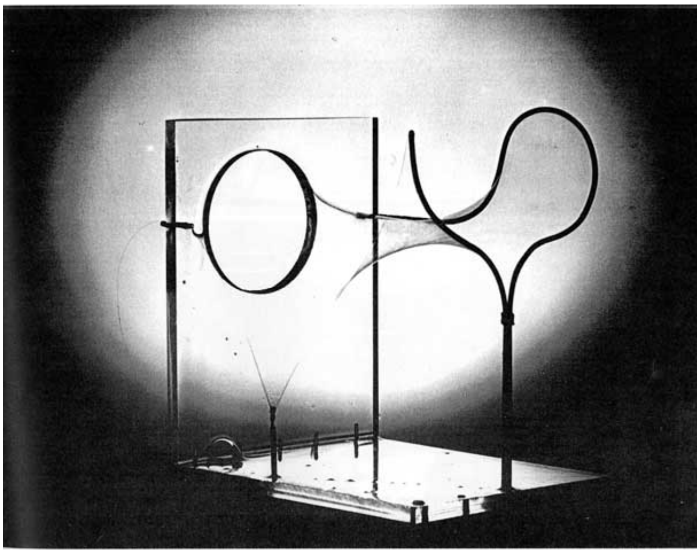
Chains and chains-net

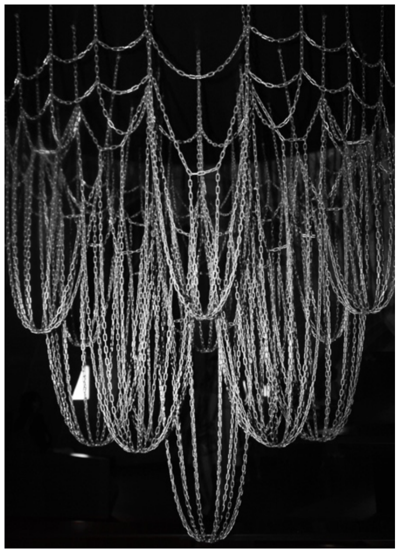
A method that explores form for structures, mainly in compression, using suspended chains and its own weight and gravity to find the "ideal" shape for the structure. This method has been known and used in construction for centuries, and can be seen in several roof structures all over the world, for example Sagrada Familia in Barcelona by Antonio Gaudi, see Figure 5-2. This method was also used for the pavilion for the Bundesgartenschau in Mannheim, Germany and several shells structure by Frei Otto.

By pulling the chains in different ways and with different boundary conditions, new forms with both compression and tension, curved and double curved shaped can be designed in a natural way.

Plaster bandages
By using medical plaster bandages, it is possible to design free form structures, see Figure 5-3. The method is similar to the chain and chain-set method, then this also using suspended material. The advantages with plaster bandages compare to chains is that it hardens and becomes rigid and stiff when it reacts with water. When that happens the structure can be turned up-side-down and a new shape with another structural behaviour is created. This shape can easily be translated into a real structure, especially for concrete and wood. The method results in realistic shapes for constructions and has been used in form-finding processes for roof, arches, and bridges.

Heinz Isler another structural art engineer, describe in his paper "New Shapes for Shells" from 1959 three methods for finding new complex form which are similar to Frei Otto's methods; the free hill shape, the membrane under pressure and the hanging cloth reserved, which he worked with entirely in his working life, i.e. no computational models were used (Chilton, 2010).





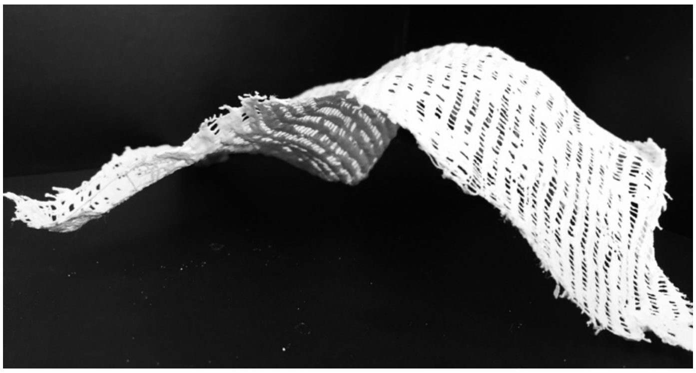


Figure 5-2. Above: Chains-net creating a natural form. This structure is a model for La Sagrada de Famila. (Photo: Ellen Simonsson).

Figure 5-3. To left: Shell of plaster bandage. (Photo: Ellen Simonsson)

Figure 5-1. Top left: Soap film model created by Frei Otto. (Photo: Institut fuer Leichtbau Entwerfen und Konstruieren).

5.1.2 Digital Models

A digital model is an alternative way to design and is suitable when using the simple mathematical geometry method which Mangelsdorf, 2010 describe in the Journal *Architectural Design*. During the last decades different software have been developed to analyse the structure, both aesthetical and structural behaviour.

When the design, shape and material are decided the digital model can be analysed. The internal stresses can be determined from certain data, both for the global structure and smaller elements within the structure. This type of model is called *computational model.* With a computational model it is possible to develop the design according to the structural behaviour and action as moments, stresses and forces within the structure.

5.2 Design Methods in Thesis

From theory about the material, manufacturing and different design techniques, an appropriate design method was selected to work with in this thesis. The elected method was a combination between form-finding, simple mathematical geometry and free form method. Mangelsdorf (2010) describes this as the Hybrid Approach, where physical form finding is translated into a mathematical model, in order to find the optimal structural geometry without losing the aesthetic concept.

The Hybrid Approach is an iterative process which is based on design, analysis and improvement, with a constant dialogue between structural behaviour and aesthetic, leading to a final structure (Mangelsdorf, 2010).

Both physical and digital models were used in order to understand the shape, structural behaviour and the material during the process.
Figure 5-4 shows the overall process and the process scheme, on next page describe the process in more detail.

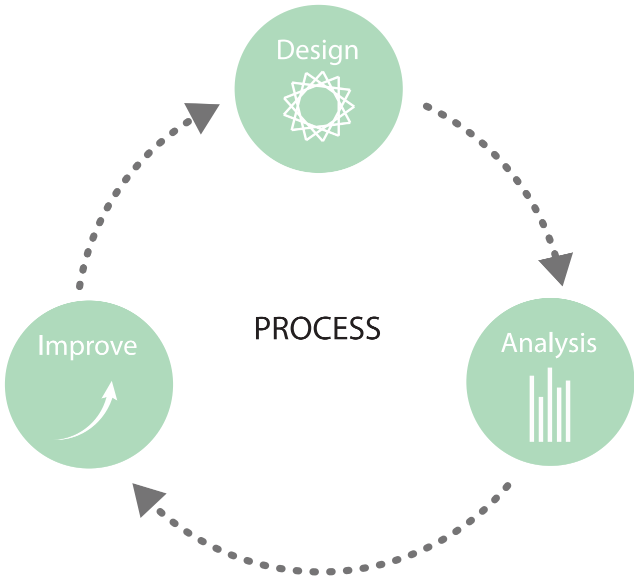
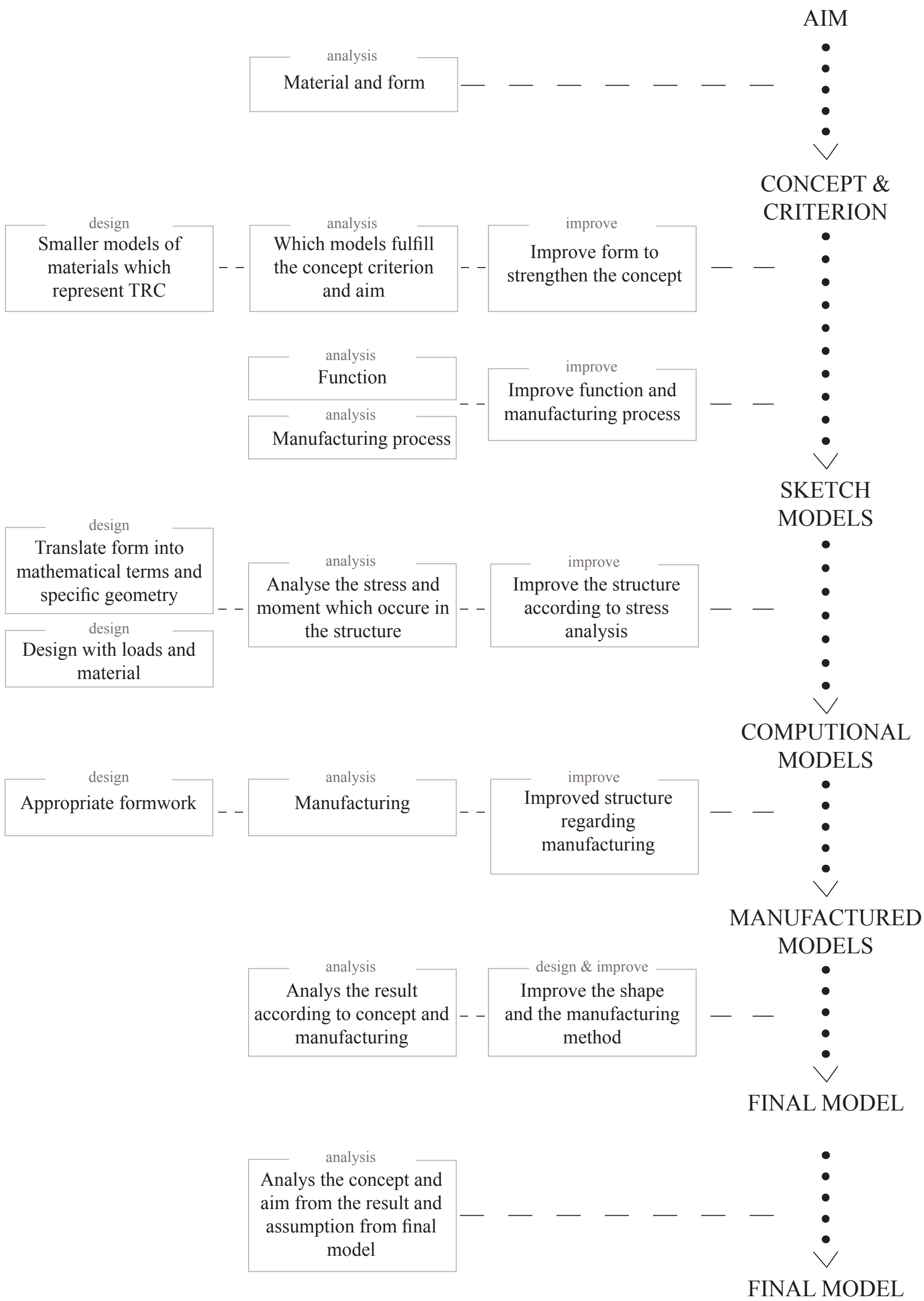


Figure 5-4. The working process is iterative where design, analysis and improvement will be three different states in the process.

5.2.1 Process


AIM
analysis
Material and form
CONCEPT & CRITERION
design
Smaller models of materials which represent TRC
analysis
Which models fulfill the concept criterion and aim
improve
Improve form to strengthen the concept
analysis
Function
analysis
Manufacturing process
improve
Improve function and manufacturing process
SKETCH MODELS
design
Translate form into mathematical terms and specific geometry
design
Design with loads and material
analysis
Analyse the stress and moment which occure in the structure
improve
Improve the structure according to stress analysis
COMPUTIONAL MODELS
design
Appropriate formwork
analysis
Manufacturing
improve
Improved structure regarding manufacturing
MANUFACTURED MODELS
analysis
Analys the result according to concept and manufacturing
design & improve
Improve the shape and the manufacturing method
FINAL MODEL
analysis
Analys the concept and aim from the result and assumption from final model
FINAL MODEL

6 Smaller Physical Models

Physical models are a tool for the *free form* and *form-finding* method, and in this thesis, this tool was chosen to be applied in the design process. In the first stage, the aim for the physical models were to communicate aesthetical form combined with an underlying structural system for TRC.

Sketches, main concept and criteria worked as a foundation and the smaller physical models were created with materials which represent TRC in a smaller scale. The models were assumed to give quick answers and raise questions about shape, material and manufacturing possibilities.

From this investigation several design opportunities and difficulties were identified.

6.1 Concept and Design Criteria

In this stage, the function for the form was neglected. The forms were only created by the material's properties i.e. the design had limitation and possibilities which reflected on the material's behaviour.

To reflect the material's properties, the structures had to be designed from the main concept; *thin, strong and interesting shape*.

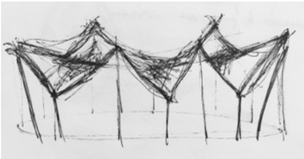
The design criteria were guidance during the design- and evaluation phase for the models. The structures should fulfil the criteria, and the most promising ones were then developed further. In the list below, the criteria for the smaller physical models are listed without any priority order.

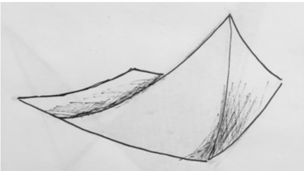
- The structure shall join architectural form and engineering solutions.
- The structure shall widen the possibilities of concrete structures.
- It is preferable if the structure would be difficult to cast with steel bars as reinforcement.
- The manufacturing procedure shall be identified and possible to do at Chalmers' concrete lab.
- It is preferable to continue the work with three different functionalities and manufacturing methods.

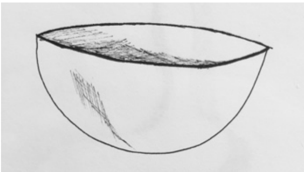
6.2 Conceptual Design

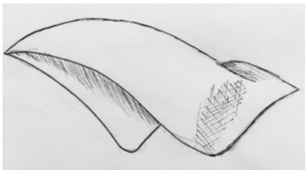
Due to the structural properties of TRC, thin and curved structures are possible to create. The fine-grained cement that has to be used, results in a smooth surface and increases the possibilities to create forms with sharp edges. Due to the fact that textile has a high strength capacity in tension and concrete in compression, the material can be used in different structural behaviour. However, structures in compression have a better load capacity.

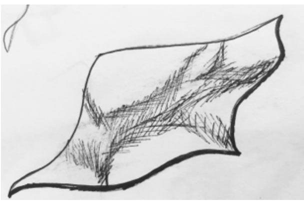
With this in mind several forms were designed and the following seven categories were studied:


Form of tensioned fabric

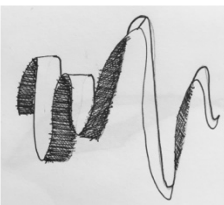

Folded forms


Forms with round openings


Shell structures


Double curved surfaces


Twisted forms


Forms of stripes

6.3 Methods and Physical Models

The aim of creating smaller physical models was to rise questions of the global structure, the material and the manufacturing procedure and the models were designed with different methods to investigate these aspects. The materials which were chosen in the investigation had comparable behaviour (in a small scale) as TRC and could therefore represent the material well. The methods were chosen regarding to TRC's behaviour and variations of forms it is suitable for.

Following, the form categories from chapter 6.2 are explored with form-finding- and free form method, and the result from the investigations is described.

6.3.1 Form-finding

The forms that were created, came from the material itself and the extrinsic forces, hence; the structures were in equilibrium both internal and external. This method is suitable for all kind of materials, but particularly TRC and other materials which can be used for structures with curvatures and irregular forms. In this case, fabric and plaster bandages were used as materials in the physical models.

Form of tensioned fabric
For the investigation of *form of tensioned fabric*, plaster and fabric were used as materials. The materials and method was based on the *plaster-bandage-method* described in section 5.1.1. Here the textile represents the reinforcement and the cement the concrete.

The fabric, in this case nylon, stretches in different forms and creates various types of double curved and tensioned structures. Similar to textile reinforcement, the fabric has a high tension strength and no compression capacity. The supports are in compression. By adding a layer of plaster on the fabric, the structure become stiff, and works in compression as well, hence no supports are needed to keep the form. The fabric has similar properties as pre-tensioned reinforcement and therefore the plaster will act in compression when the structure is unloaded.

This method of pre-tensioned reinforcement can be preferable, especially in cases where the structure is subjected to loads which lead to high tensile stresses.

From this investigation if was found that there are two main advantages with the method. First, the variations of forms are wide due to the fabrics flexibility. Second, it is possible to easily make a quick test of both structural behaviour and aesthetic expression.

An optimization of the forms has to be done to ensure a structure in balance in further investigation for these forms. Also, the manufacturing procedure needs to be considered: how the textile reinforcement can be stretched and how it effects the internal forces in the concrete. Two examples are shown in Figure 6-1 and 6-2.

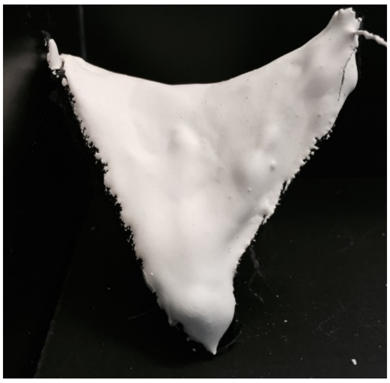


Figure 6-1. Hyperbola-structure of nylon and plaster. (Photo: Ellen Simonsson)

Figure 6-2. Double curved structure of nylon and plaster. (Photo: Ellen Simonsson)

Twisted forms

Plaster bandage was used in these models which is stiff stripes that become flexible in reaction with water, and hard when the material dries. Compared to nylon, it is good in tension but cannot be stretched in the same manner, hence; the variations of forms are not as wide. The benefit with the material is that it becomes stiff when the material has dried, i.e. it works in compression, similar to the tensioned fabric structures with plaster. From the test, some questions were raised regarding the reinforcements shear capacity. Equal to textile reinforcement the bandages can be bend in both direction, but its shear capacity is low. By dividing the material in smaller stripes, such that each smaller stripe can be more or less planar, disadvantages due to shear can be solved. This solution can be seen as an irregular surfaces divided in several planes with a small twist. The same approach was assumed to be suitable for textile reinforcement. The reinforcement can be divided in smaller pieces and placed overlapped in order to get full capacity. The size of the pieces is dependent on the shear capacity and how strong the twist is in the aimed shape. See Figure 6-3 and 6-4 for two examples of twisted forms.

Figure 6-3. Twisted form of plaster bandage. (Photo: Ellen Simonsson).

Figure 6-4. Twisted form of plaster bandage. (Photo: Ellen Simonsson).

Shell structures

Various types of shell structures are easily made with form-finding method. Plaster bandages and fabric are pinned in different forms and are placed up-side-down to achieve a form from the gravity force, similar to the chain method. Depending on how the bandages or the fabric are pinned i.e. the boundary conditions, different shells are created. The material and the force are the main components which are decisive in the form searching but the chosen boundary conditions are also of major importance and makes it possible to design different forms.

During the design process, the shell was mainly designed in tension and when turning the structure up-side-down, it became a structure in mainly compression as in the chain method.

The results were often simple structures which were in balance with both inner and outer forces. The room under the shell had different appearance depending on the form, but it was often spacious with a lot of possibilities.

The manufacturing for these kind of structures can be done in several ways e.g. grid shell-, foam models- and with formwork of fabric.

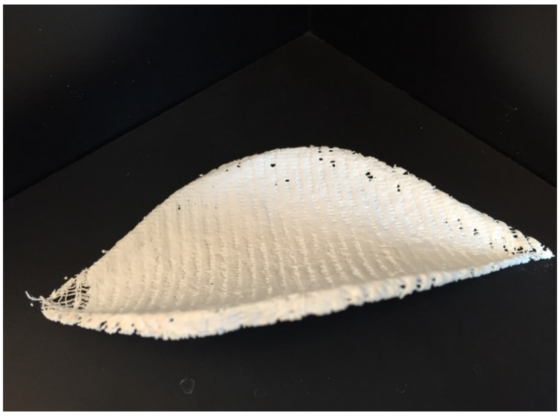


Figure 6-5. Shell formed as a curved leave. (Photo: Ellen Simonsson).

Figure 6-6. Shell of plaster bandages with four supports. (Photo: Ellen Simonsson)

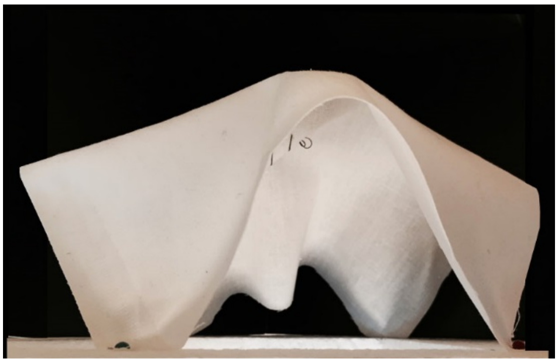


Figure 6-7. Same structure as shown in Figure 6-7 but upside down creates a shell in compression. (Photo: Ellen Simonsson).

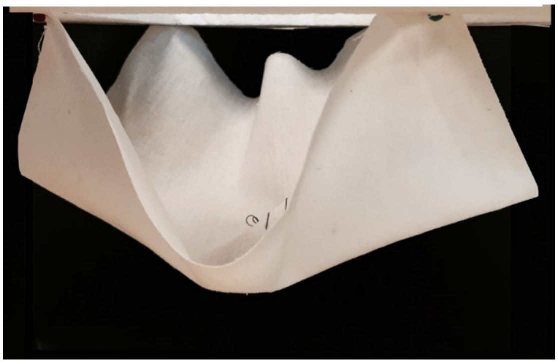


Figure 6-8. Tension structure of fabric with a fold. (Photo: Ellen Simonsson)

6.3.2 Free form

When designing free form structures there is no considerations of external forces. Compared to form-finding, the structure can be forced to a specific form. Materials used in this method were aluminium wire-net and plaster bandages. The aluminium wire-net has a similar bend behaviour as textile reinforcement and the plaster bandages have great variations in form similar concrete. These materials are therefore suitable for conceptual models for TRC structures with free form method.

Folded form

It is easy to manufacture TRC structures with plane surfaces as in folded forms. The reinforcement can be placed easily in the right direction. Also, sharp edges which is a result of folding, is suitable for TRC, therefore it is interesting to investigate these kind of structures.

Depending on the manufacturing procedure there are questions that need to be further investigated. If the structure will be divided into several elements, the connection details and how forces will be transferred have to be solved. If the structure is cast as a unit, the bending behaviour of the reinforcement is of main importance to take into consideration when it is a risk that it breaks in the sharp edges. In Figure 6-9 and 6-10 two examples are shown.

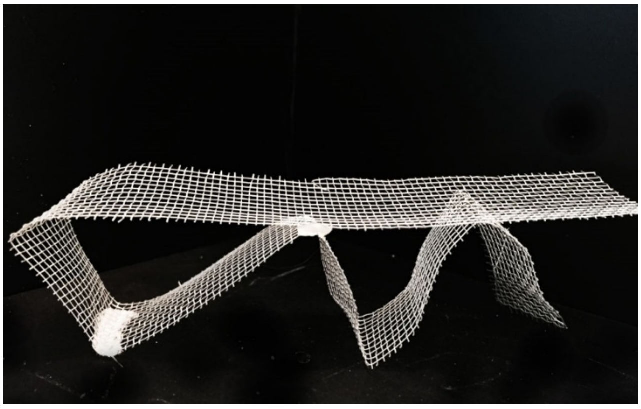


Figure 6-9. Continuous folded structure. (Photo: Ellen Simonsson).

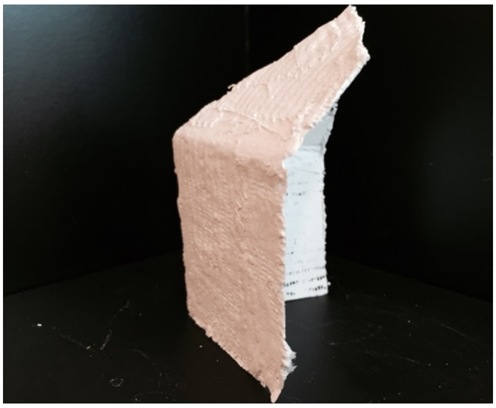
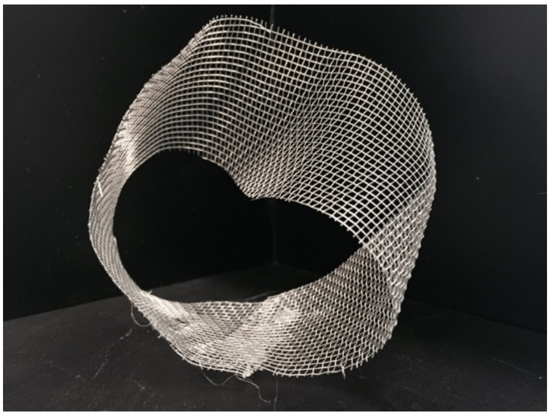
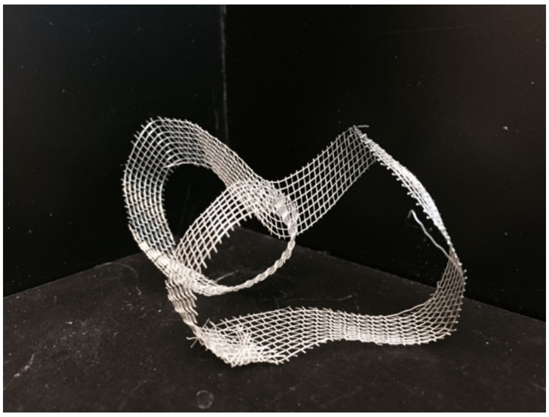


Figure 6-10. Plane surfaces connected. (Photo: Ellen Simonsson).

Twisted forms

The twisted models shown in Figure 6-11, 6-12 and 6-13, highlight the same questions and possibilities as the ones designed by the form-finding method. The material used in the models was aluminium wire net, which is more flexible in shear compared to plaster bandages, hence these models have almost no limitation regarding shear. This needs to be taken into consideration when developing these types of structures further, hence the behaviour in shear will be different.





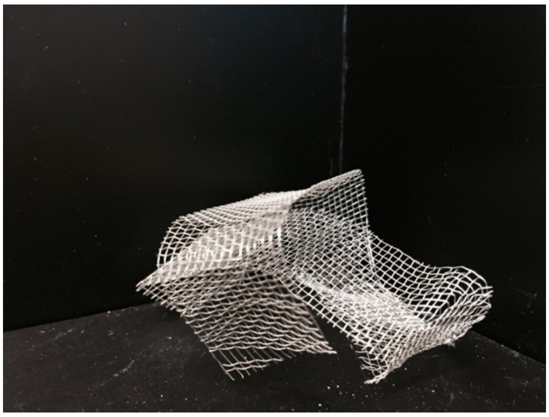


Figure 6-11. Twisted from 1. (Photo: Ellen Simonsson)

Figure 6-12. Twisted form 2. (Photo: Ellen Simonsson)

Figure 6-13. Twisted form 3. (Photo: Ellen Simonsson)

Forms of stripes

Textile reinforcement is manufactured and produced as long coiled net, similar to fabric, and follow the form of the textile reinforcement. The bending capacity of reinforcement is decisive regarding the form and how sharp the curves can be without breaking the reinforcement. If the design has sharp curves it can be possible to divide the reinforcement, but to ensure the capacity it has to overlap which can be problematic in very sharp curves.

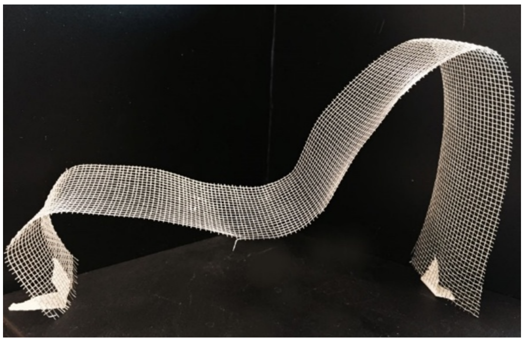


Figure 6-14. Stripe with three curves. (Photo: Ellen Simonsson)

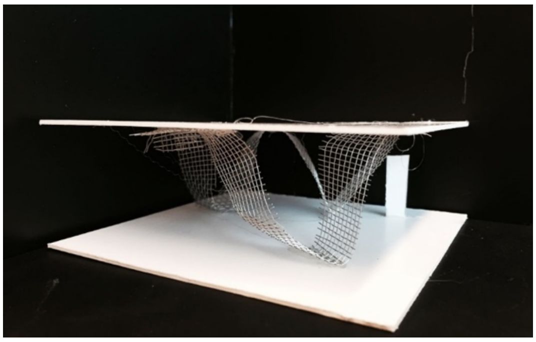


Figure 6-15. Stripes with several sharp curves. (Photo: Ellen Simonsson)

Forms with round opening(s)

Textile reinforcement can be bent and placed in correct direction. Structures with curved tensile stresses, for example circles, can therefore be suitable for TRC. Following structures are both double curved and have circle holes, forms which are difficult to design with steel bar reinforcement.

The models are made of plaster bandages which have gotten its form of a foam globe. This method was also assumed to be good for greater scale with TRC.

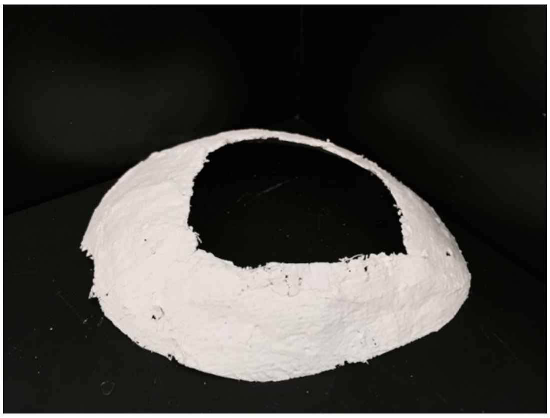


Figure 6-16.
Figure 6-17.
Figure 6-18. Different types of domes made of plaster bandages. (Photo Ellen Simonsson)

Double curved surfaces/volumes

As mentioned, TRC shows good possibilities in free formed double curved structures, but the manufacturing procedure, especially for these kind of structures, has to be considered early in the design stage. With too complex form it can be preferable to divide the surface in several elements instead of casting it as a whole unit. Connection details then need to be considered and solved.

Figure 6-19. Double curved surface made of plaster bandage. (Photo: Ellen Simonsson)

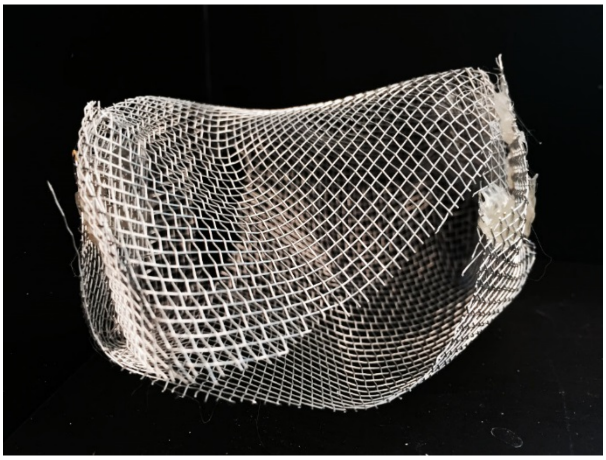


Figure 6-20. Double curved surface made of aluminum net. (Photo: Ellen Simonsson)

6.4 Evaluation

The models were evaluated according to the main concept and the design criteria. The concept *thin, strong and interesting shape* were a thought in all models in the design process, hence all models fitted more or less to the concept and no convincing elimination could be made from this. The evaluation continued with the criteria, and when no ranking of the criteria was made it become an iterative process. Starting with the aesthetical appearance, continued with discussion about how the form is structural interesting for TRC and if the form could highlight new structural form of concrete. The evaluation finished with a realistic analysis of manufacturing, scale and function. It was preferable to have a function possible to manufacture in a 1:1 model. This process was made until five promising models were left. To ensure a diversity of the models, the final step was to choose three forms with different functionalities and manufacturing procedures.

The three most promising models were:

- The Chair
- The Dome
- The Sculpture

Following, the models are described in detail.

6.4.1 The Chair

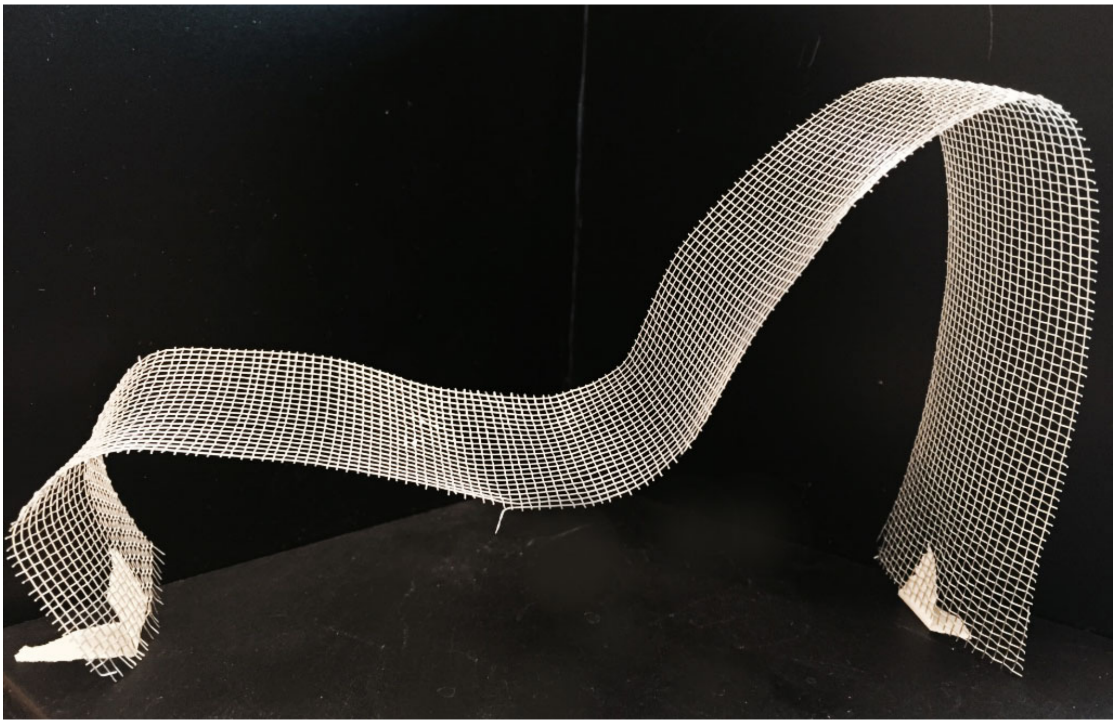


Figure 6-21. The small conceptual model of The Chair. (Photo: Ellen Simonsson).

Aesthetic

The stripe creates a form like a wave. It is simple, continuous and it has a frozen movement in its form.

Structural

It is both tension and compression within the structure due to the curvatures.

Form for TRC

Concrete in these kind of structures are not common, but is possible to do if the curvature is not too sharp. The thickness of the structure is a part of the appearance and with TRC it is possible to create a thin section, which highlights, not just the structure but also the possibilities of TRC to create thin structures.

Manufacturing

It was assumed that this structure could be manufactured with the casting method. A foam-form can be made and the reinforcement will be placed in the formwork before casting.

Function and Scale

The structure will be a chair. Development of the form according to the function will be done further in the thesis. An estimated measurement is approximately 1.2 x 0.6 x 1.4 m.

6.4.2 The Dome

Figure 6-22. The small conceptual model of The Dome. (Photo: Ellen Simonsson)

Aesthetic

A classic form with a twist. A dome with a tilted opening in the top. The spatial appearance in the dome is interesting and can work in many functionalities and scales, from a bowl to a great arena.

Structural

When loaded, the upper circle will be in compression and the lower circle in tension. There will also be some bending moment in the structure.

Form for TRC

Textile reinforcement is assumed to be easily, compared to steel bars, placed in right direction along this double curved surface, at the tension circle and where the moment will occur.

Manufacturing

The model was made by plaster bandage wrapped around a half foam sphere. This method could be used for TRC as well. The concrete and reinforcement will be applied at a form with the lamination method, in the same matter as the plaster bandages. The surface towards the formwork was assumed to be the same as the form and the outer side more rough depending on the accuracy during manufacture.

Function and Scale

The function for the structure was chosen to be mechanical and the investigation was chosen to focus on the assumption if the reinforcement can be easily placed in the right direction and as a circle.

6.4.3 The Sculpture

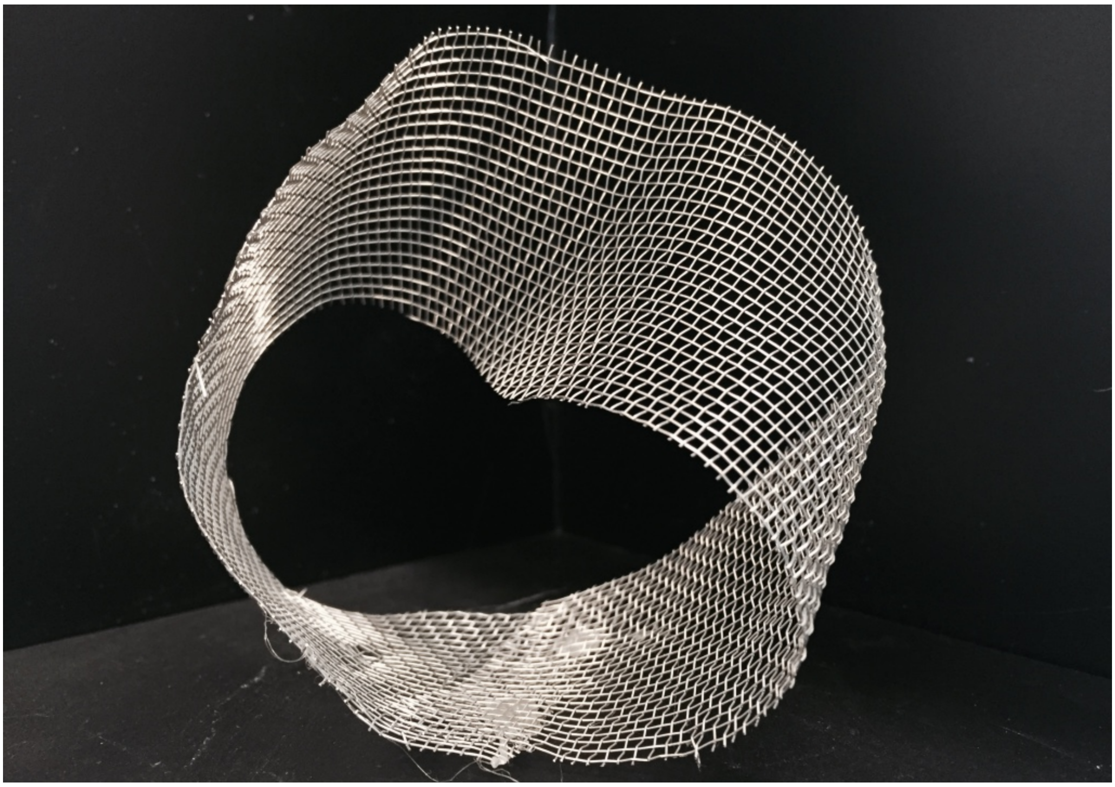


Figure 6-23. The small conceptual model of The Sculpture. (Photo: Ellen Simonsson)

Aesthetic

Interesting and a continuous form, which has different appearance from different angels.

Structural

It is both shear and bending in the structural form, and the section will change in the structure.

Form for TRC

It is assumed to be difficult to manufacture a structure with this kind of design with ordinary reinforcement, especially if the cross section is thin. Therefore, it is likely that this structure will highlight the material and to widen the possibilities of concrete design.

Manufacturing

To manufacture this structure a combination of pultrusion and lamination method will be used. The lamination method is suitable for more complex forms and therefore suitable for this structure. The textile will work both as reinforcement and as the mould, and concrete will be applied on both side of the textile. In Figure 6-24 this concept of manufacturing is shown.

The fresh concrete needs to have low followability since it will be spread evenly on the mould, which can decrease the bonding between the reinforcement and concrete. This is a disadvantage but has a small effect on the structure, since it does not require a very high strength due to its function.

Figure 6-24. Conceptual manufacturing model of basalt textile reinforcement and plaster. (Photo: Ellen Simonsson)

Function and Scale

It will be designed further as a sculpture i.e. it should be designed just for its own weight, with the purpose to highlight TRC's wide design possibilities.

7 Computational Models

7.1 Digital Working Tools

If correct measurements should have been taken from the small models in Chapter 6, formwork could have been made and the structures be manufactured. Heinz Isler, a structural engineer famous for his design of concrete shells, worked with this process in all his works (Chilton 2010). But, in order to analyse the structural behaviour and to compute and improve stresses, a digital model is necessary. With given shape, boundary conditions, load and material properties it is possible to create a mesh of numbers of elements and nodes, such that the internal forces and displacements can be estimated. This method was used in the thesis to determine both the global structure and the cross section design.

The design process continued in a computational model to analyse and optimize the structure according to internal forces and other factors as weight and manufacturing procedure.

The 3D modelling tool Rhinoceros and the plugin Grasshopper were used when creating the form. In Figure 7-1 the working view of Rhinoceros is showed. The four different views are plan, elevation in two directions and perspective. The form which is showed has nothing do to with the three chosen models.

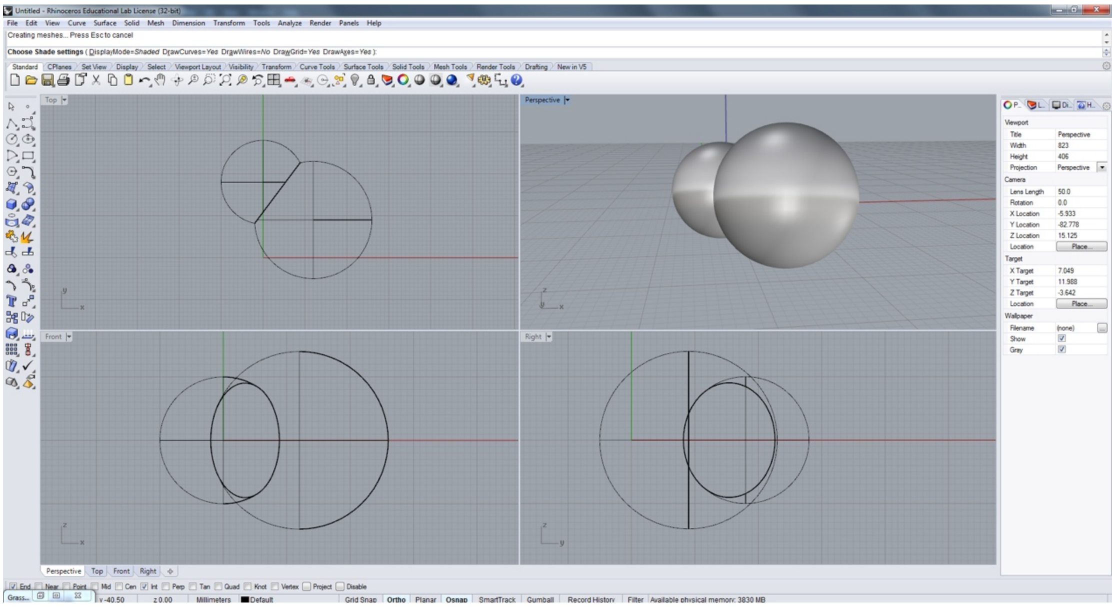


Figure 7-1. The working view in Rhinoceros.

The structures were further analysed in Karamba, a plugin to Grasshopper. Karamba is a parametric engineering tool for analyse structures like shells, trusses and frames. The software is preferable when designing more complex shapes and therefore chosen to work with in this thesis. In Figure 7-2 it is shown how a form created in Grasshopper (to right) is showed in Rhinoceros (to left) and how the shape creates a mesh in Grasshopper which Karamba analysis.

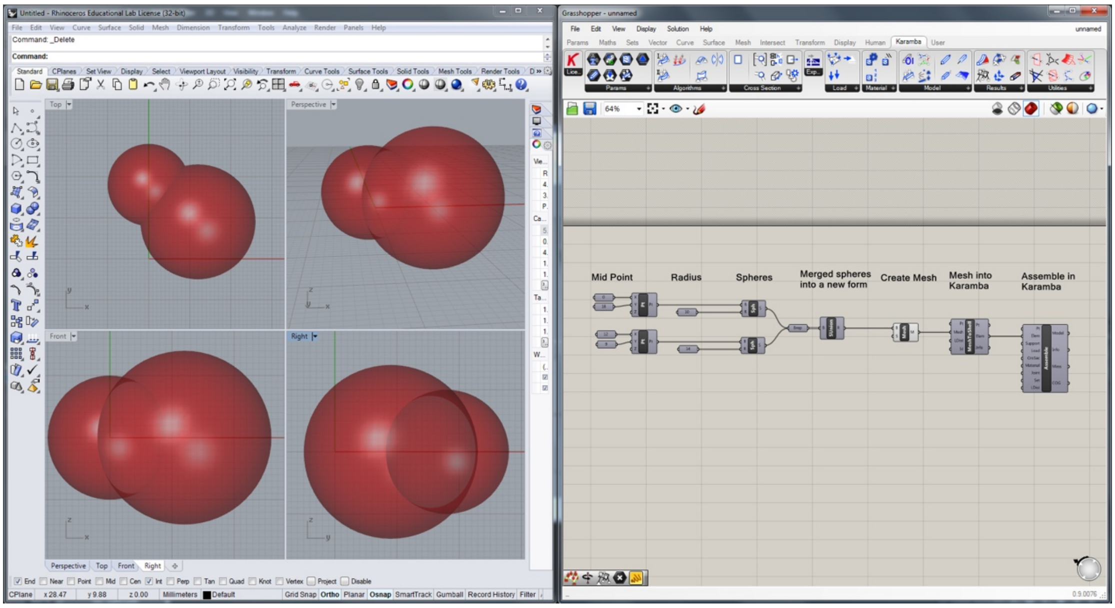


Figure 7-2. A screen shoot of Rhino, Grasshopper and Karamba which illustrates the working process.

When the maximum moment and tensile stress in the structure is identified the reinforcement can be estimated, both the numbers of yarns and placement. With this information, the whole structure is designed. The process was iterative, i.e. the form was developed until the aimed internal forces were reached.

There are two main advantages to use a stress analyse program which is a plugin to Grasshopper where the design is made. Firstly, the form does not need to be exported, hence there are no risks for uncertainties in the design. Secondly, it is easy to change the design according to the stress field and load cases when the results are shown directly.

7.2 The Chair

7.2.1 Model

The smaller model was redesigned according to function. With measurements of a 1.70-meter person, the height and length of heel, knee, bottom, back and head were stated. From this data a curve, illustrating the length section was made, see Figure 7-3. The first iteration of the form as a digital model is shown in Figure 7-4.

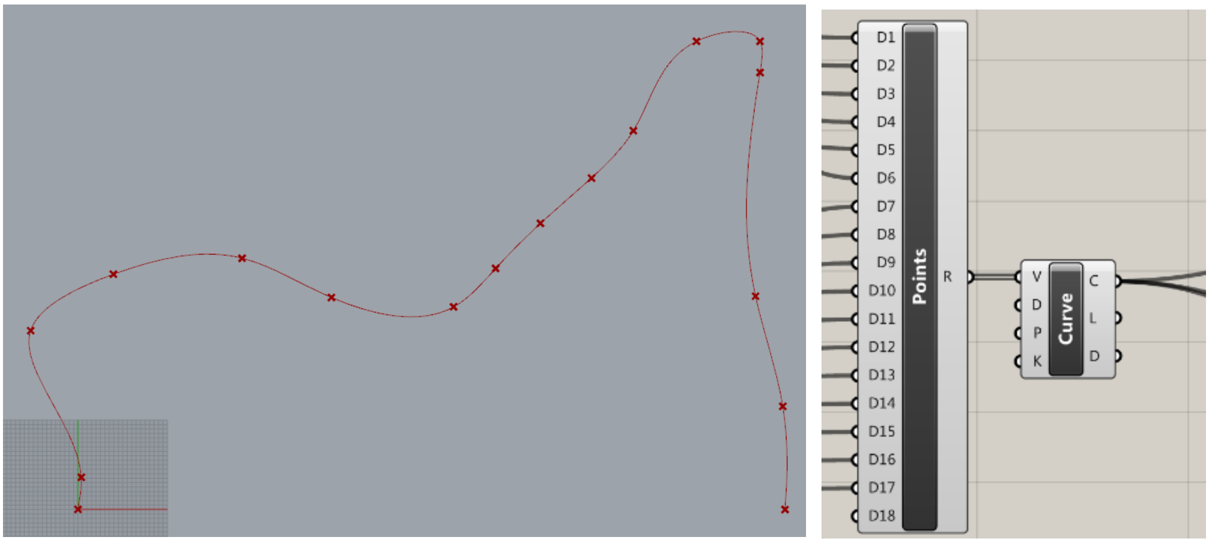


Figure 7-3. The structure was created from points placed according to body parts and dimensions of a person of 1.70 m. From the points, a curve was created.

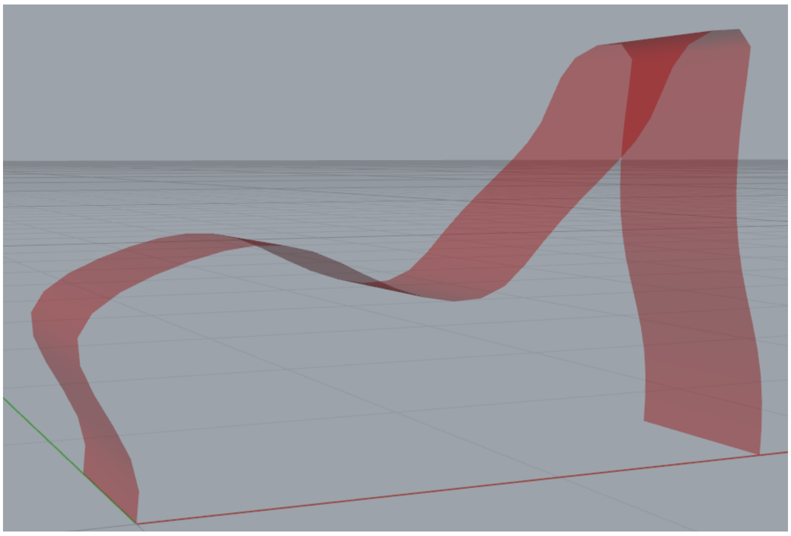


Figure 7-4. First iteration of model.

7.2.2 Structural Behaviour

To analyse the structure, a triangular mesh with 1000 elements was created. Loads and boundary conditions were stated. The boundary condition was set to simple supported and can be seen in Figure 7-5. The boundary conditions were fixed in the left end in translation and free in rotation in two directions and fixed in y- and z-translation in the right end.

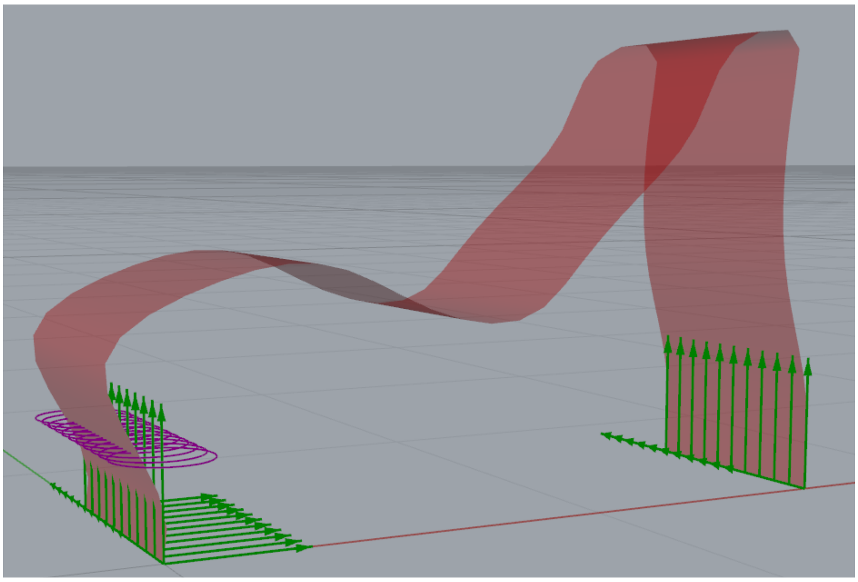


Figure 7-5. Simple supported boundary conditions.

The structure was analysed with three different load cases which were expected for the structure's function.

1. Self-load
2. Load when a person is sitting
3. Load when a person sits down

In Figure 7-6 and Figure 7-7 load case 2 and 3 are shown.

The self-load was estimated by the volume of concrete and its density.

$$G = l \times h \times b \times \rho \times g \text{ N} \tag{7.1}$$

Where

l = lenght of curve [m]

h = height of cross section [m]

b = width [m]

ρ = density of concrete = 2400 [kg/m^3]

g = gravity force = 9.81 [m/s^2]

The load from a person will not be evenly distributed hence the sit position and therefore the load was divided into three parts. The parts were divided according to: leg, bottom and back. For load case 2, the weight of a person was divided as seen below.

$$P_{\text{leg}} = \frac{W \times g}{12} \text{ N} \tag{7.2}$$

$$P_{\text{bot}} = \frac{2W \times g}{3} \text{ N} \tag{7.3}$$

$$P_{\text{back}} = \frac{W \times g}{4} \text{ N} \tag{7.4}$$

Where

W = weigth of person = 90 [kg]

This distribution of the load was approximately according to how the weight of a person is distributed when sitting, and was assumed. The load is acting at the chair as seen in Figure 7-6. For load case 3 the whole weight acts in the middle (the bottom part), as seen in Figure 7-7.

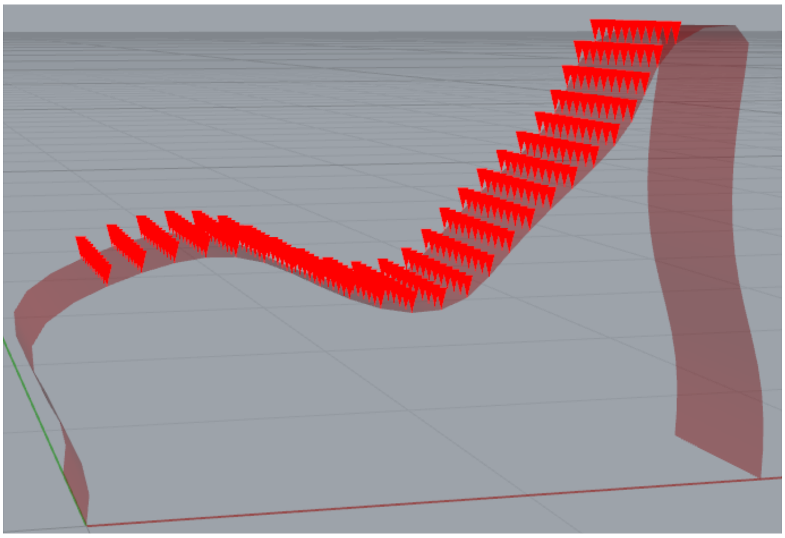


Figure 7-6. Load case 2, when a person is sitting on the chair.

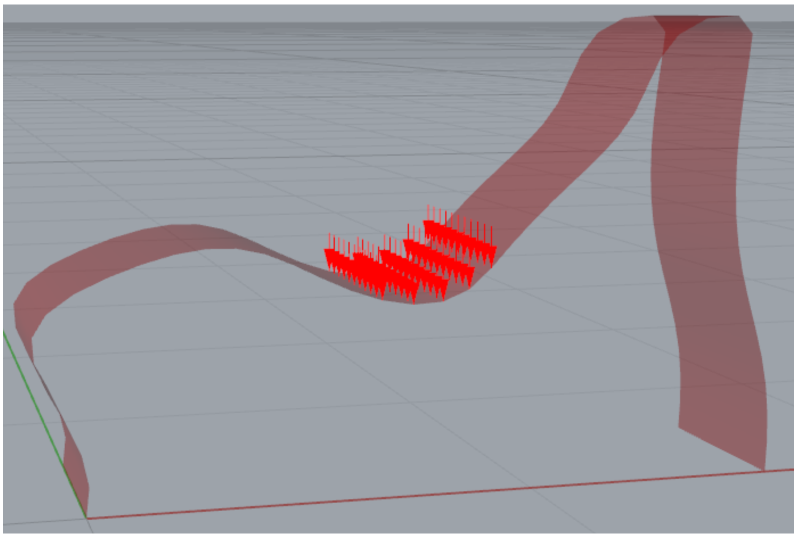


Figure 7-7. Load case 3, when a person sits down on the chair.

For load case 2 and 3 the total load was estimated in Ultimate Limit State (ULS) over the whole length of the curve according to equation 7.5 and 7.6, where Q is the total load acting on the structure.

$$Q = \sum_{0}^{l} 1.35G + \sum_{\text{leg}} 1.5P_{\text{leg}} + \sum_{\text{bottom}} 1.5P_{\text{bottom}} + \sum_{\text{back}} 1.5P_{\text{back}} \tag{7.5}$$

$$Q = \sum_{0}^{l} 1.35G + \sum_{\text{bottom}} 1.5(P_{\text{bottom}} + P_{\text{leg}} + P_{\text{back}}) \tag{7.6}$$

In order to make the manufacturing process not too complex, the cross section was designed consistent and with the same amount and placements of the reinforcement. Hence; the whole structure was designed according to the most critical cross section where the maximum tensile stress and moment occurred.

Moment and tensile stresses were estimated for all three load cases and the maximum values are presented in Table 7.1.

Table 7.1. Result from first iteration

	Value	Load Case
Maximum tensile stress	1.03 kN/cm^2	3
Maximum moment	0.785 kNm	3
Cross section thickness	3 cm	-
Width	50 cm	-
Weight	132 kg	-

7.2.3 Developed Structure

The procedure to find the final shape was an iterative process which continued until the aim was reached. The form was developed with the aim to reduce tensile stress parts and to reach a lower maximum tensile stress and moment. The weight was also preferable to be lower due to practical and handy reason during manufacturing. Still, the chair needs to retain its function, i.e. the dimensions of leg- and back length, some angles and height must (more or less) be maintained. Figure 7-8 and Figure 7-9 shows the structure before and after developing.

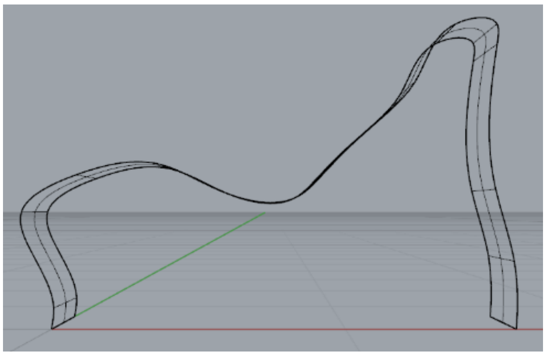


Figure 7-8. Form before development.

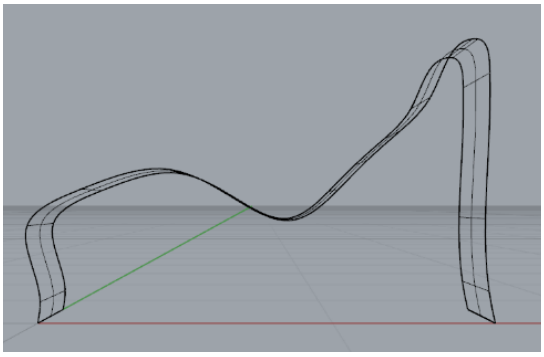


Figure 7-9. Form after development.

The developed form had new maximum tension stress, displacement, moment and weight, all improved from the previous shape. This was the second iteration, and could have been designed further to reach better results.

The result, from both before and after changes, are presented in Table 7.2.

Table 7.2. Results before and after development.

	Before development	After development	$\frac{\text{Before}}{\text{After}}$
Maximum tensile stress	1.03 kN/cm^2	0.703 kN/cm^2	47%
Maximum moment	0.785kNm	0.53kNm	48%
Cross section thickness	3 cm	3 cm	-
Width	50 cm	55 cm	-
Weight	132 kg	129 kg	2.3%

The first principal stress distribution for load case 3 in the upper- and lower part of the cross section are shown in Figure 7-10 and Figure 7-11. The red and blue colour represent compression respective tension stress. All analyses were made with a consistent cross section of three centimetres.

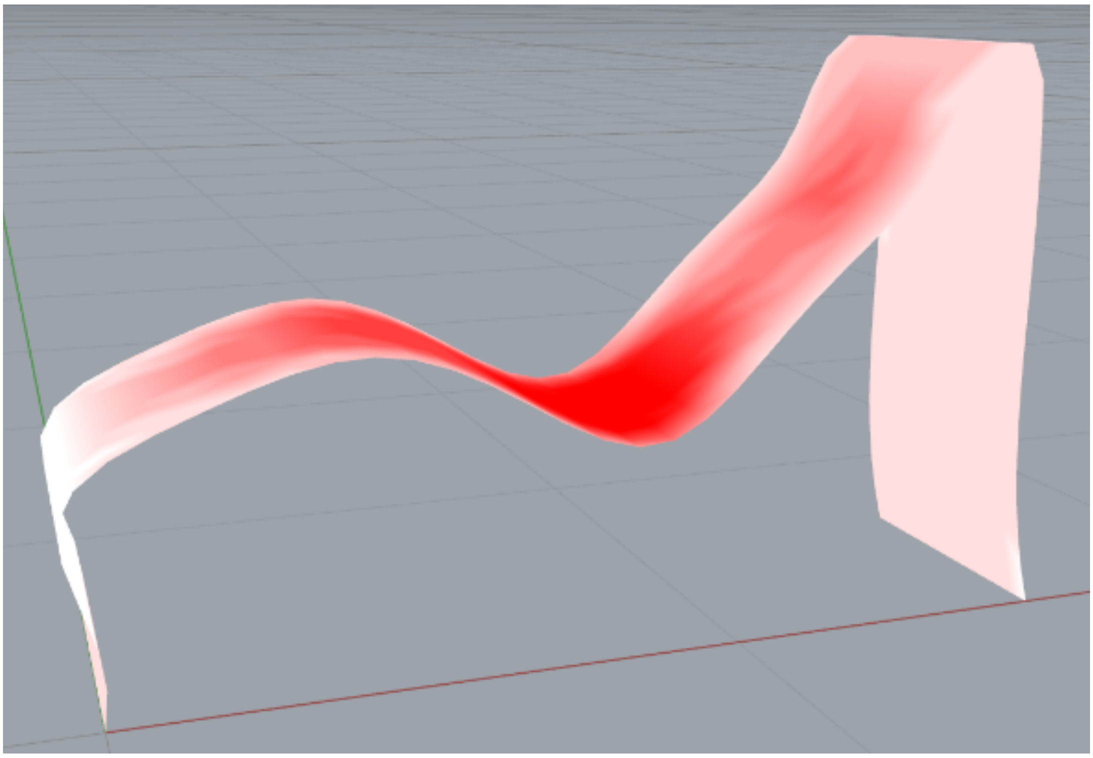


Figure 7-10. Upper stress distribution for principal stress 1, the whole upper part is in compression.

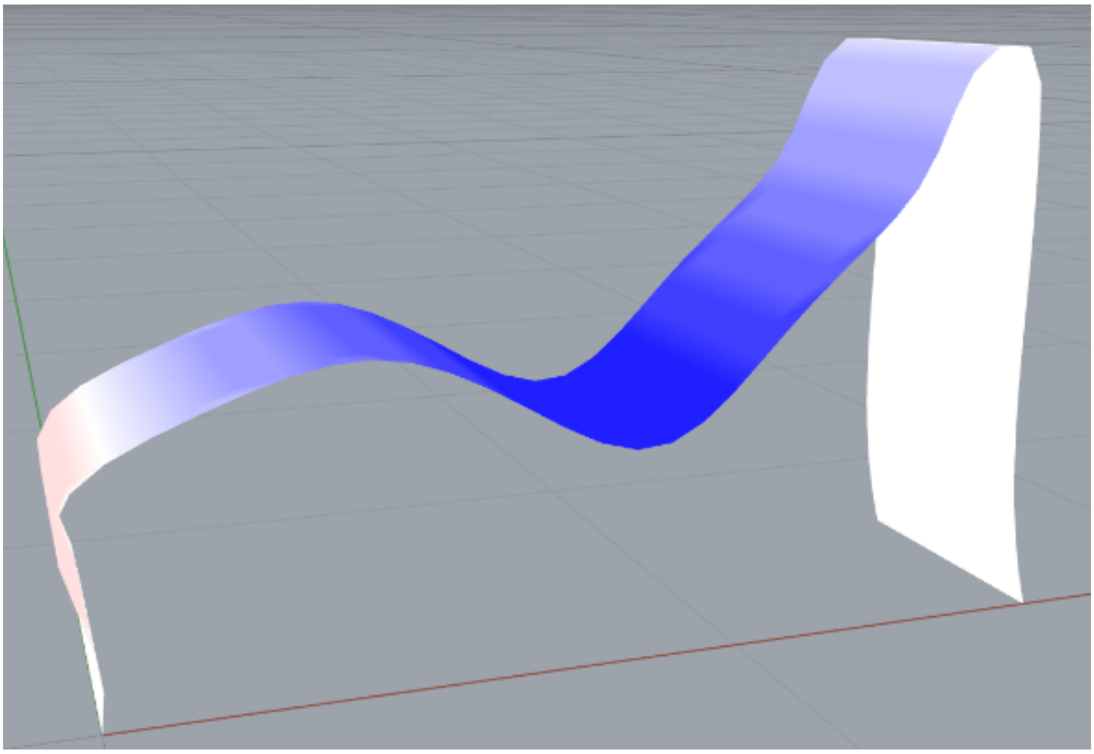


Figure 7-11. Lower stress distribution for principal stress 1, most of the bottom part is in tension.

7.2.4 Cross section design

In order to design a cross section that should be able to handle the moment, the placement and numbers of yarns were estimated. Expression 7.7 needed to be fulfilled.

$$M_{\mathrm{Rd}} \geq M_{\mathrm{Ed}} = 545Nm \tag{7.7}$$

The design moment M_{Rd} was estimated by the process explained further and the value of M_{Ed} was estimated in Karamba.

In order to estimate the reinforcement according to the bending moment in Ultimate Limit State, ULS, equation 7.8, 7.9 and 7.10 were used. In equation 7.9 the compression zone is estimated when assuming a full layer of yarns.

Number of yarns in one layer

$$\frac{b}{d_y} = n \tag{7.8}$$

Where

b=width of cross section

d_y=distance between yarns

Find compression zone x, see Figure 7-12

$$\alpha \times f_{\mathrm{cd}} \times b \times x = f_{\mathrm{b}} \times n \tag{7.9}$$

f_b is the tensile force capacity of one yarn basalt fibre which was chosen for all structures and is approximately 1 kN.

Design moment:

$$M_{\mathrm{Rd}} = \alpha \times f_{\mathrm{cd}} \times b \times x(d - \beta \times x) \tag{7.10}$$

$$f_{\mathrm{cd}} = \alpha_{\mathrm{cc}} \times \frac{f_{\mathrm{ck}}}{\gamma_{\mathrm{c}}} \tag{7.11}$$

Where

f_{ck}=compression strength for concrete 30/37

γ_{c}=partial coefficient (=1,5)

α_{cc}= 1,0

α=0.81

β=0.416

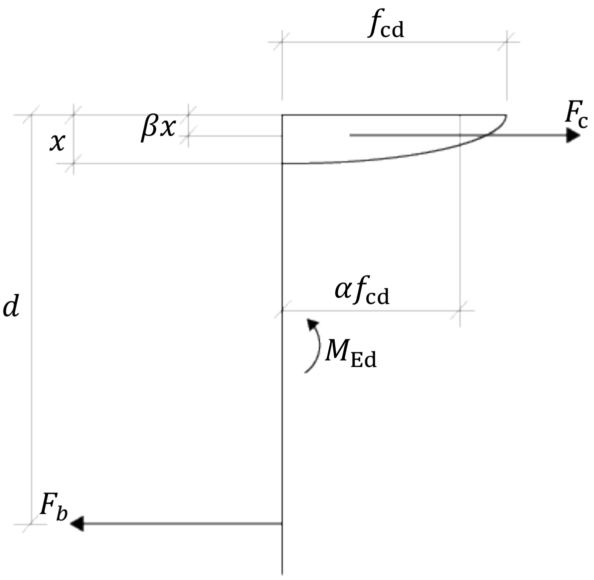


Figure 7-12. Stress distribution according to the working curve of concrete.

Check the expression 7.7

$$\frac{M_{Rd}}{M_{Ed}} = 1{,}07 \geq 1 \tag{7.12}$$

The expression was fulfilled.

Result of design:

For the first iteration of the design it would have been necessary to have two layers of reinforcement, due to higher moment and shorter width. For the second iteration, 17 yarns were needed to handle the maximum moment which can be placed in one layer, which was preferable. To ensure the capacity in edges the cross section was designed with a full layer of reinforcement.

The cross section design is shown in Figure 7-13. The final design with dimension is shown in Figure 7-14.

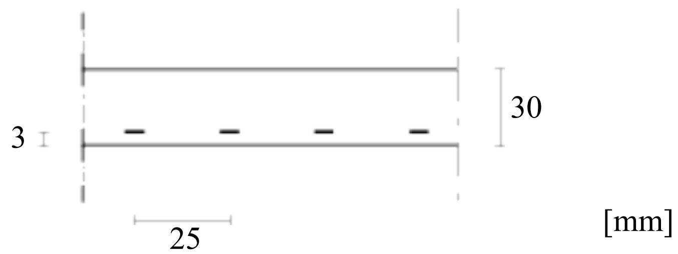


Figure 7-13. Cross section design

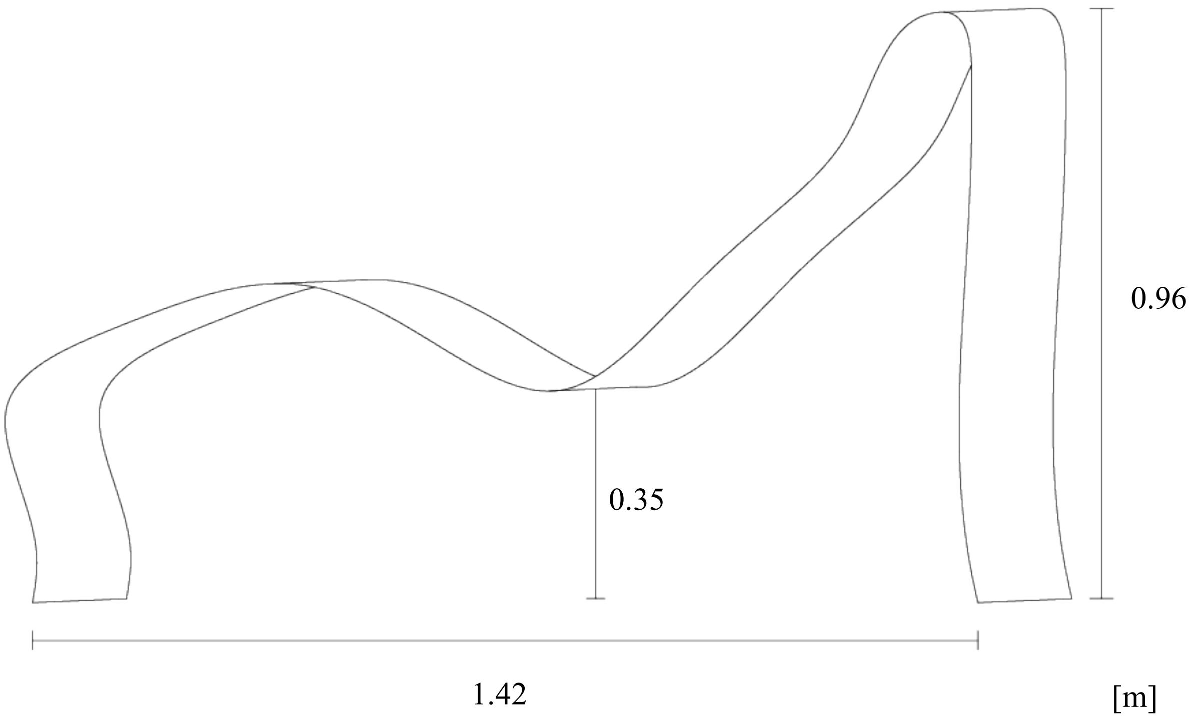


Figure 7-14. Final form with dimensions.

7.3 The Dome

7.3.1 Computational Digital Model

The main purpose to design a dome with TRC was to investigate the manufacturing and how the reinforcement could be placed.

Due to the fact that the function of this dome was structural there were no requirements of dimension or measurement in the same manner as for *The Chair*. The decisive value of dimension was therefore the weight, which should be reasonable to handle during the manufacturing, as well as to to find an aesthetical form with high strength capacity.

The model was created with parameters in Grasshopper, starting with a sphere with a radius of 0.8 metre. The sphere was then cut by two planes, one flat and one tilted, see Figure 7-15. The first iteration of shape is shown in Figure 7-16.

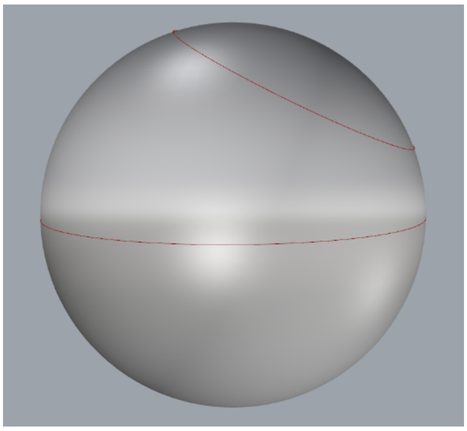


Figure 7-15. The original sphere which was trimmed by two planes.

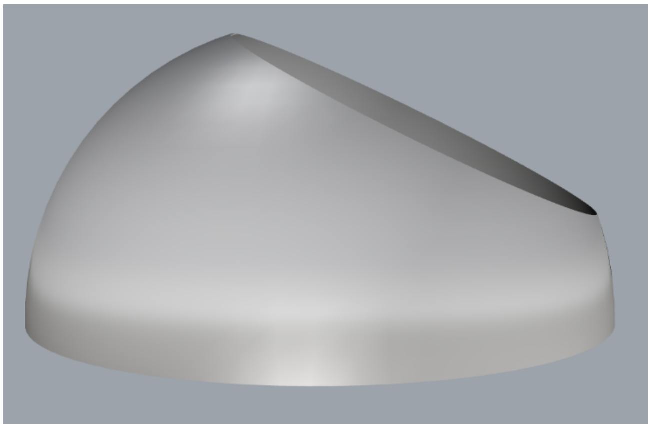


Figure 7-16. The first iteration of the form.

7.3.2 Structural Behaviour

Due to the fact that the structure did not have a clear function, there was no significance to control the structure according to a certain load as for *The Chair*. Instead, the aim of the design process was to estimate a load P, which the structure with a chosen thickness and chosen amount of reinforcement could handle. For the same reason as for *The Chair,* the cross section was designed consistently. Over the whole structure, one layer of reinforcement was chosen to be placed in the middle of the cross section and the thickness of the structure was chosen to be 2 cm.

The form was analysed in the same manner as for the chair; created in Grasshopper and then translated into a mesh which was estimated in Karamba.

The boundary condition is shown in Figure 7-17 and Figure 7-18. The node (x,y,z)=(0,0,0) was fixed in all translation and in z-rotation. The node (x,y,z)=(2 x radius,0,0) was fixed in y- and z-direction. The other nodes with (z) = (0) were fixed in z-direction and in z-rotation. These boundary conditions let the structure move as it was placed on a non-frictional ground which lead to higher stress values then in reality.

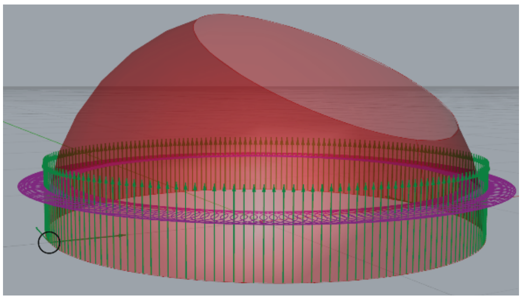


Figure 7-17. Marked node (x,y,z)=(0,0,0)

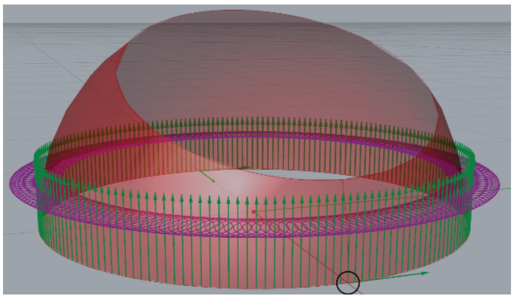


*Figure 7-18. Marked node (x,y,z)=(2*r,0,0)*

The dome was analysed for three different load cases.

1. Self-load
2. Point load at the top, distributed on the top circle
3. Load acting on the whole surface

Load case 2 and 3 is shown in Figure 7-20 and Figure 7-19. For load case 2, the total load P is evenly distributed along the upper circle.

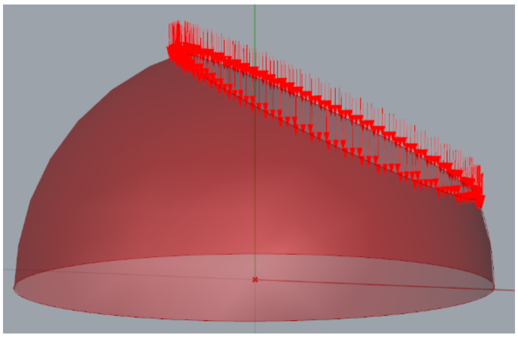


Figure 7-20. Load case 2.

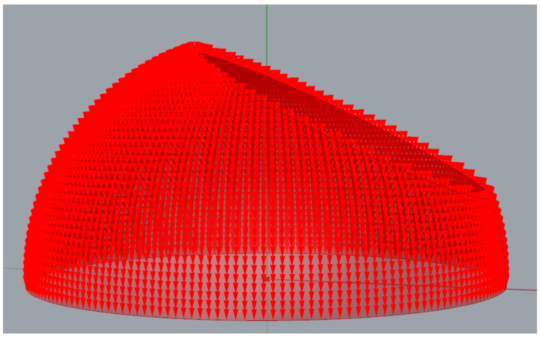


Figure 7-19. Load case 3.

To find the most critical load case, i.e. the load case when the highest moment and tension occur in the structure, an assumed load p where used.

When analysing the structural behaviour for the three load cases, a tensile stress circle in the bottom and a moment were found in the dome.

The first principal stress at the outer side of the mesh is shown for load case 1 respectively load case 2 in Figure 7-22 and Figure 7-21, where blue indicates tension, red compression.

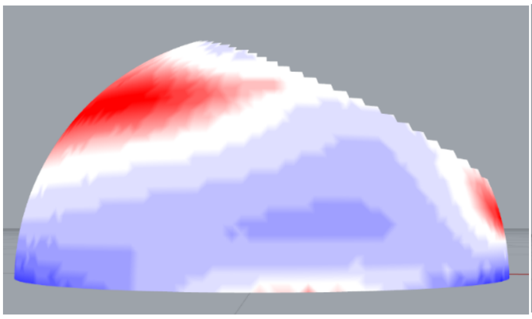


Figure 7-22. Stress distribution for load case 1.

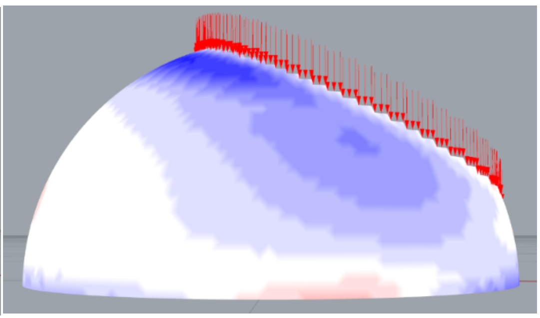


Figure 7-21. Stress distribution for load case 2.

7.3.3 Control calculation

Load case 2 resulted in the greatest internal forces for load p, therefore; the following control calculations were made for load case 2. The aim for this calculations was to find the maximum load P, the chosen design (form, thickness and amount of reinforcement) could handle. The calculations were made for the tension circle in the bottom and the moment in the middle of the dome.

Tension circle

The maximum load P (shown in Figure 7-25 and Figure 7-24) was estimated by finding maximum stress in the tension circle that one yarn could handle (one layer of reinforcement was chosen). The cross section of the dome with equation variables is shown in Figure 7-23.

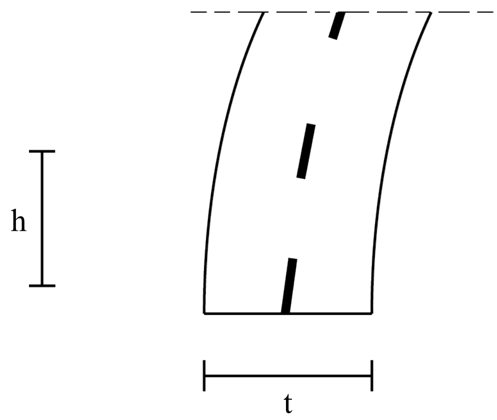


Figure 7-23. Illustration showing variables for equation.

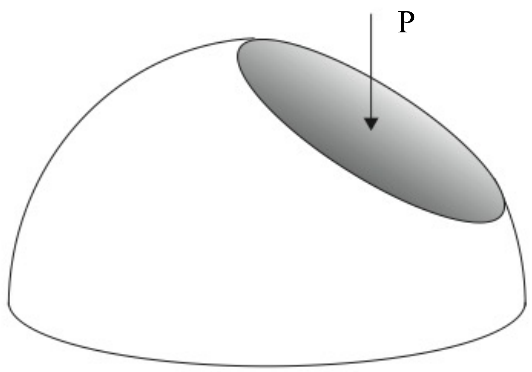


Figure 7-25. P acts in the middle of the top circle.

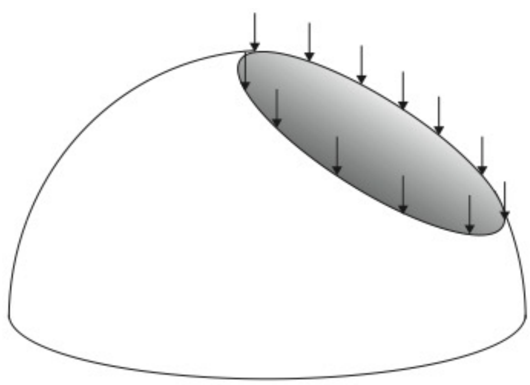


Figure 7-24. P is evenly distributed along the top circle.

$$\sigma = \frac{F_s}{A} \tag{7.13}$$

Where:

$F_s = 1$ kN

$A = h \times t = 2.5 \times 1.5 \text{ cm}^2$

This resulted in

$\sigma = 0{,}267 \text{ kN/cm}^2$

with this value, P_{tot} could be found in Karamba which corresponds to $P_{tot} = 6.5$ kN.

Moment

The area of the maximum moment is marked in Figure 7-26.

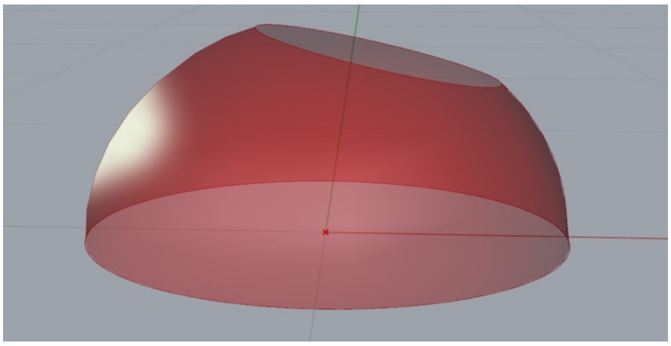


Figure 7-26 Marked area where maximum moment occurs.

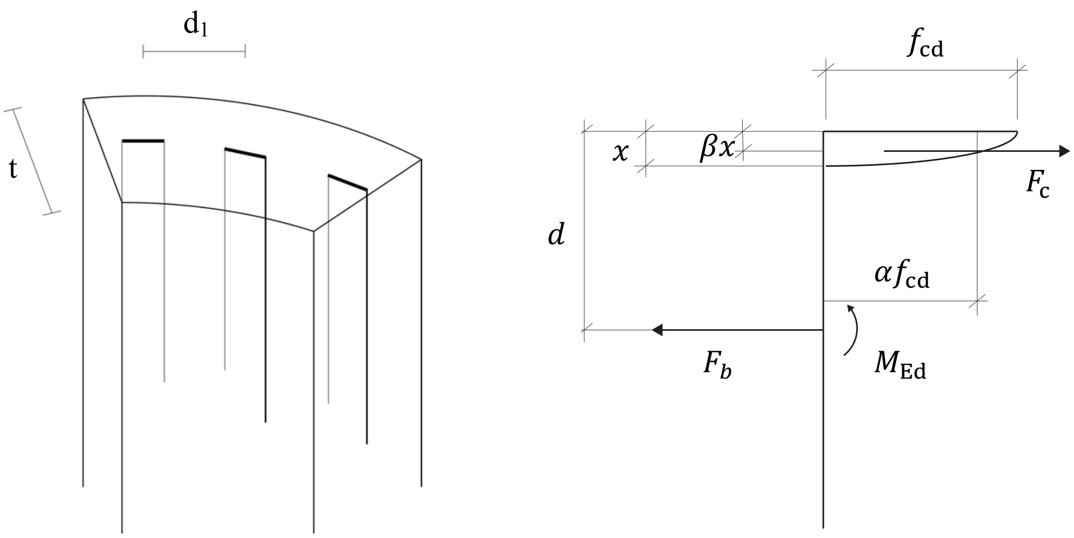


Figure 7-27. Variables description.

To ensure the structure could handle the moment from the load P=6.5 kN the expression 7.13 had to be fulfilled.

$$M_{Rd} \geq M_{Ed,P=6,5kN} = 295Nm \tag{7.14}$$

The amount of yarns that could be placed at the top circle

$$n = \frac{c}{d_1} \tag{7.15}$$

Where

$c = 1{,}58\ m =$ circumference where maximum moment occure found in Karamba

$$\alpha \times f_{\mathrm{cd}} \times c \times x = f_{\mathrm{b}} \times n \tag{7.16}$$

f_b is the tensile force capacity of one yarn basalt fibre is approximately 1 kN.

Design moment:

$$M_{\mathrm{Rd}} = \alpha \times f_{\mathrm{cd}} \times c \times x (d - \beta \times x) \tag{7.17}$$

$$f_{\mathrm{cd}} = \alpha_{\mathrm{cc}} \times \frac{f_{\mathrm{ck}}}{\gamma_{\mathrm{c}}} \tag{7.18}$$

Control of expression 7.13

$$\frac{M_{\mathrm{Rd}}}{M_{\mathrm{Ed}}} = 1.4 \geq 1 \tag{7.19}$$

Expression 7.14 was fulfilled. The amount of reinforcement was able to handle both the tension stress in the bottom circle and the moment which occur in load case 2 when P=6.5 kN.

7.3.4 Developed Structure

By changing the opening at the top of the dome the structural behaviour changed and the most efficient structure, i.e. the structure which was able to handle the highest load was a structure without opening. A dome without an opening was the most structural efficient, but the shape-concept found in the small plaster model should be lost if the opening was removed. To compromise, the structure got a smaller opening with a lower slope, see Figure 7-28

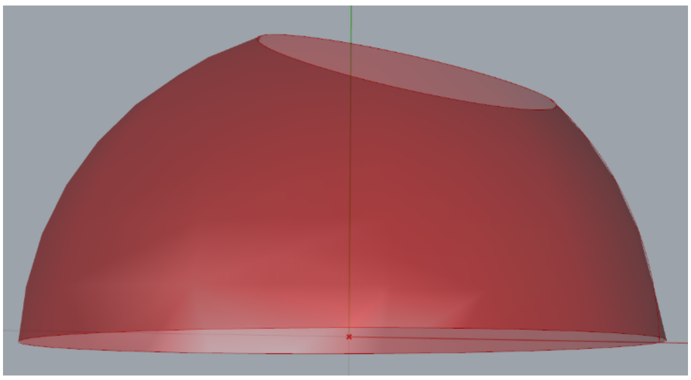


Figure 7-28. Second iteration with a smaller opening at the top.

The critical load for this shape was P=9.3 kN and was estimated in the same manner as described earlier, which was an improvement of 43% in strength capacity.

Due to the manufacturing procedure, it was assumed to be preferable to have a lower slope at the bottom of the dome, hence; for the lamination method it is easier to apply concrete if the surface is more horizontal. Therefore, the sphere in Figure 7-15 was cut, instead of in the middle, further way up, see Figure 7-29.

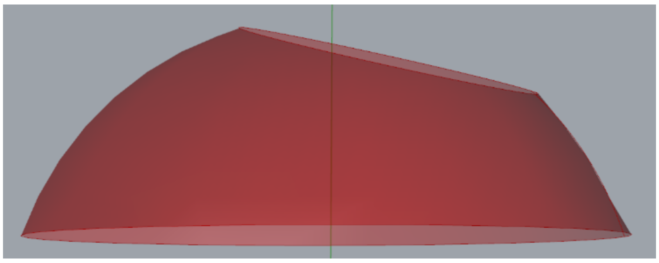


Figure 7-29. Third iteration of form due to assumed manufacturing difficulties.

The changes did not improve the structure regarding the tensile stress. Instead the tensile stress increased in area, such that the tensile circle in the bottom became wider. The structure could still be affected by P=9.3 kN. In Table 7.3 a summary of the results are shown.

Table 7.3. Result of total load and weight for first, second and third iteration.

	First Iteration	Second Iteration	Third Iteration	Improvement (first to third)
Load P	6.5 kN	9.3 kN	9.3 kN	70%
Weight	97 kg	116 kg	72 kg	36%

Result of design

Improvement in strength was made by changing the size and angle of the opening in the dome. Due to manufacturing procedure it was assumed to be preferable to have a smaller inclination at the bottom of the dome. This change increased the area of tension stresses but the value of the tension stress and moment remained the same. The reinforcement will be placed at the whole surface in right direction according to both tension in the bottom and moment in the top, see Figure 7-30.

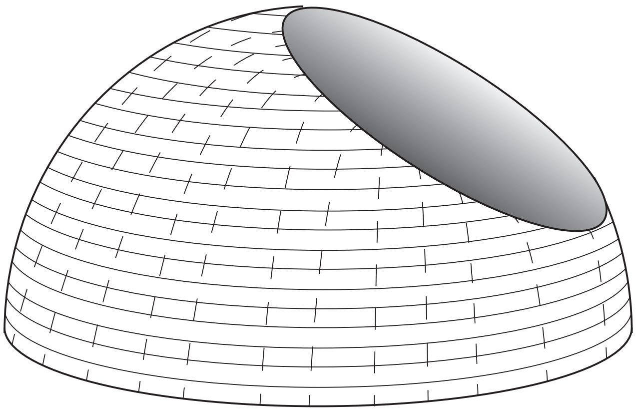


Figure 7-30. Illustration showing placement of reinforcement where dashed vertical lines correspond to reinforcement according to moment and the horizontal lines reinforcement due to tension stresses.

7.4 The Sculpture

7.4.1 Computational Digital Model

The structure was designed as a sculpture, i.e. it was only affected by its own self weight. The aim with the shape was to highlight the wide range of application of textile reinforced concrete and to investigate the combined manufacturing method. It was desirable in the design process to reach as thin structure as possible, were the flexibility of the reinforcement should be used. For the same reason as for *The Dome,* the decisive measurements were the weight and size.

The computational model was made of lines evenly distributed along a curve formed as an ellipse. To achieve the twist, each line rotated around their own axis and a surface was made from these rotated line, see Figure 7-31 and Figure 7-32. The first iteration of the shape had a width, i.e. the length of the twisted lines, of 0.55 metre and a circumference of the curve of 3.7 metre, with R_1=0.65 metre and R_2=0.55 metre. The shape is shown in Figure 7-33.

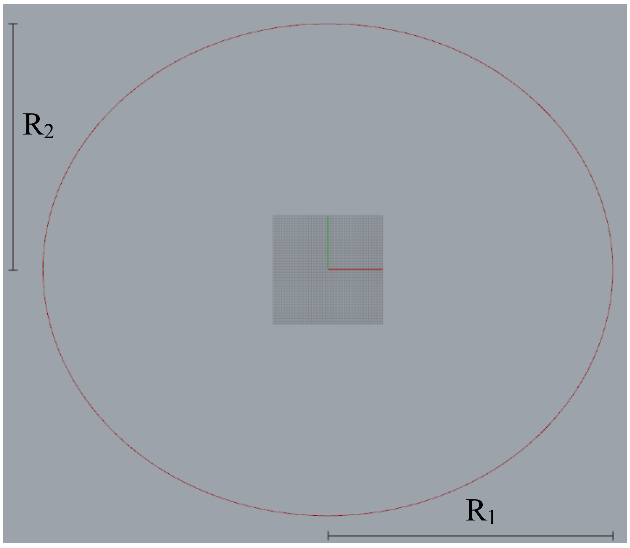


Figure 7-31. The ellipse.

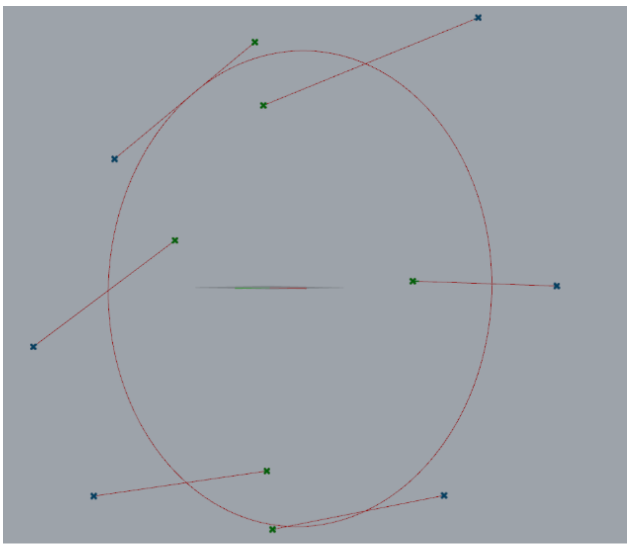


Figure 7-32. The ellipse with six evenly distributed lines which has been rotated.

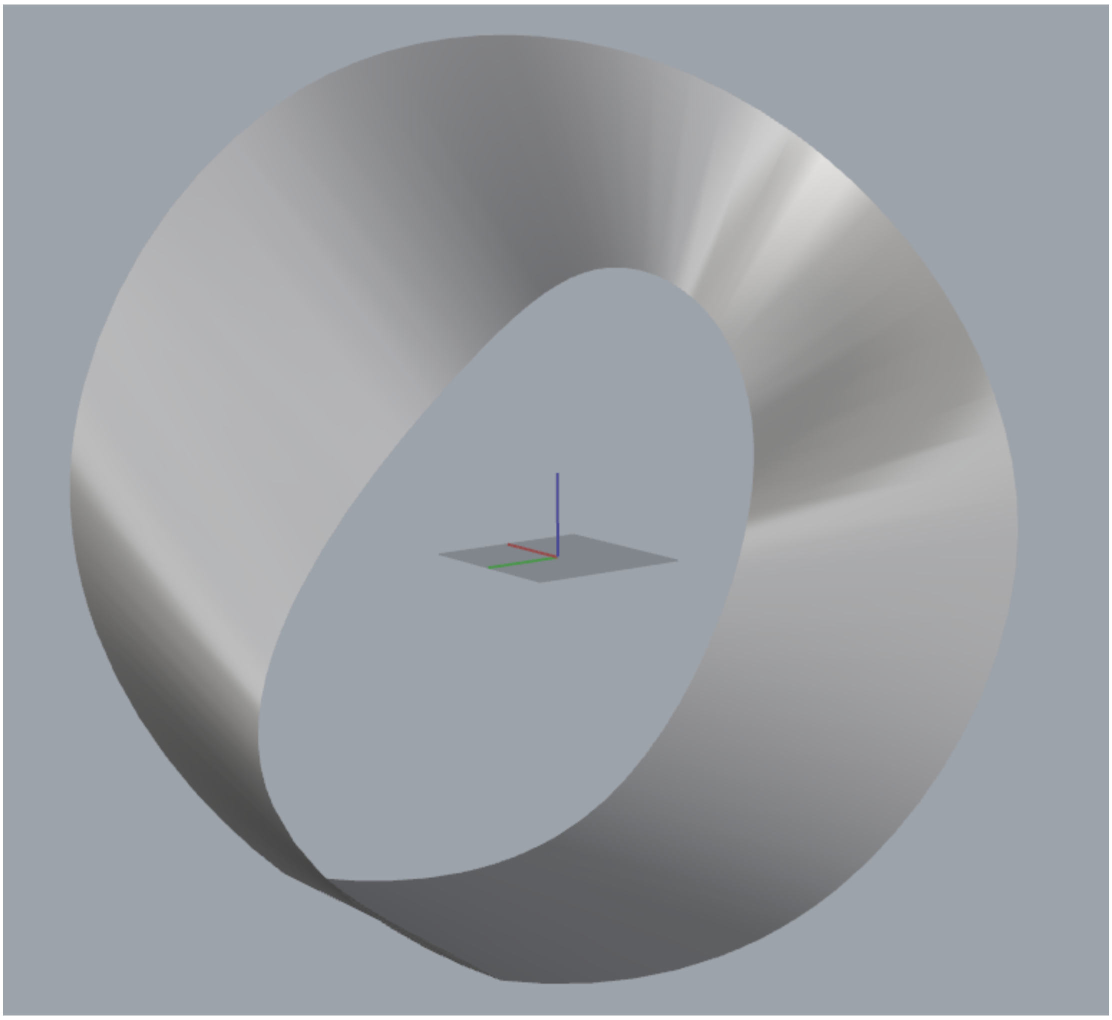


Figure 7-33. The form of the first iteration.

7.4.2 Structural Behaviour

Due to the selected manufacturing method for the structure, it was preferable to have as small holes in the open structure textile as possible. Hence, two layers of reinforcement, which overlap each other was chosen.

In the analysis, the bending moment in the structure was estimated in order to investigate if the amount of reinforcement in the structure was enough or if the structure was over-dimensioned. The analysis was made for a mesh consisted of 7400 triangular elements, and with boundary conditions shown in Figure 7-34.

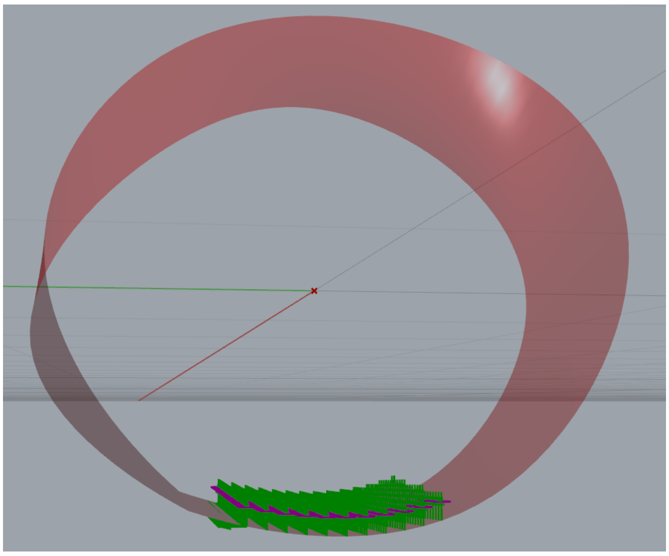


Figure 7-34. Boundary conditions.

The first principal stress is shown in Figure 7-36 and Figure 7-35, for top respectively bottom of the cross section.

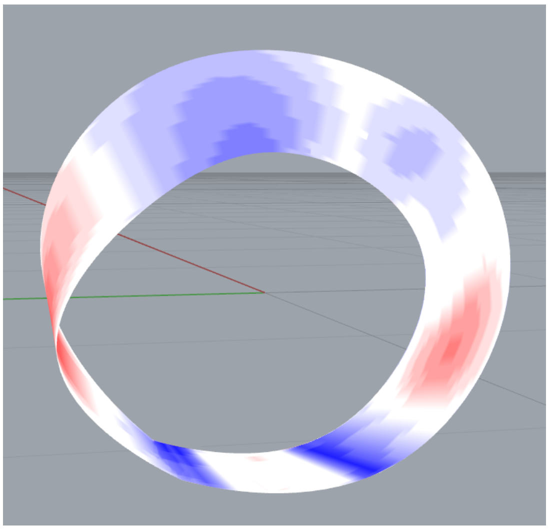


Figure 7-36. Top of mesh first principal stress.

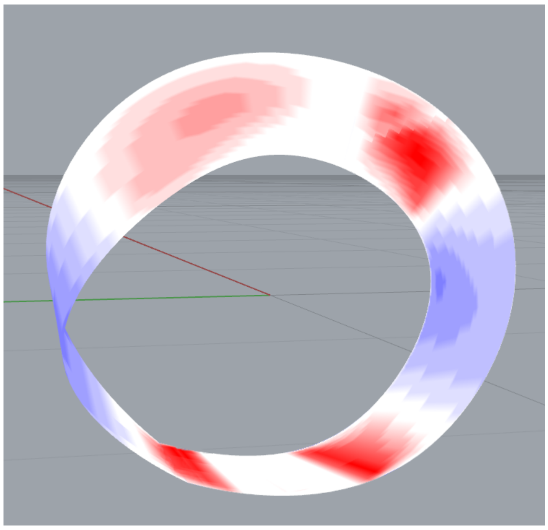
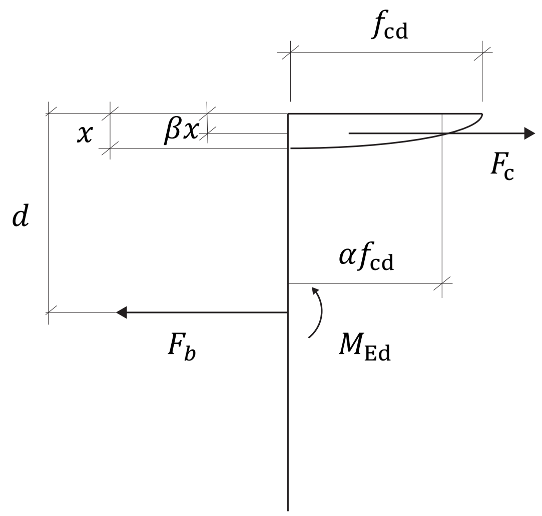


Figure 7-35. Bottom of mesh first principal stress.

As the figures shows, there will be bending moment in the structure. Therefore, the reinforcement capacity was estimated and conjucted with the maximum moment which occured in the structure. This estimation was made in stadium II for concrete.

Expression 7.20 had to be fullfilled:

$$M_{\mathrm{Rd}} \geq M_{\mathrm{Ed}} = 112Nm \tag{7.20}$$



$$F_{\mathrm{b}} = n_l \times f_{\mathrm{b}} \times \frac{b}{d_1} \tag{7.21}$$

Where

$n_l =$ number of layers

$f_{\mathrm{b}} =$ tensile strenght for one basalt yarn

$b =$ width

$d_1 =$ distance between yarns

$$\alpha \times f_{\mathrm{cd}} \times b \times x = F_{\mathrm{b}} \tag{7.22}$$

Design moment:

$$M_{\mathrm{Rd}} = \alpha \times f_{\mathrm{cd}} \times b \times x(d - \beta \times x) \tag{7.23}$$

$$f_{\mathrm{cd}} = \alpha_{\mathrm{cc}} \times \frac{f_{\mathrm{ck}}}{\gamma_{\mathrm{c}}} \tag{7.24}$$

Control of expression 7.20

$$\frac{M_{\mathrm{Rd}}}{M_{\mathrm{Ed}}} = 3.125 \geq 1 \tag{7.25}$$

The statement was fulfilled.

7.4.3 Developed Structure

From the smaller model it was learned that it was difficult to have a stiff "reinforcement-form", and therefore it was assumed that exact radius of the sculpture should be difficult to achieve. Hence, the manufacturing will be very decisive for the shape. Due to this, no improvement of the shape was made in this stage.

From the computational model it was shown that the maximum moment was decreased if $R_1 \leq R_2$. Hence, during manufacturing it was desirable to strain after a shape where $R_1 \leq R_2$, to achieve a structure with as small moment as possible

Result of design

The utilization ratio for the structure was quiet high i.e. the reinforcement amount could be decreased, but the assumption that smaller holes in the reinforcement was needed due to the manufacturing, it was decided to have two layers of reinforcement.

8 Manufacturing Small Models

As a part of the design process, the structures were manufactured in a smaller scale, approximately 1:2, with the aim to test the manufacturing method, formwork and shape of structure. From this investigation the most promising structure was developed further regarding shape, manufacturing and concrete consistence.

8.1 The Chair

8.1.1 Theory and method

The chair was manufactured with the casting method explained in Chapter 3. The reinforcement was placed at right direction and position at the formwork before casting.

The formwork was made of foam which was cut with a hot wire. The hot wire followed a closed outer curve of the shape of the chair and resulted in two parts of the foam cuboid, one upper and lower. A plastic layer was placed on both parts to ensure that the concrete could be removed from the formwork when hardened.

Reinforcement was placed on the lower part due to the mechanical behaviour of the structure. The reinforcement was placed with nails to form the reinforcement and ensure the distance from the bottom i.e. the nails worked as spacer. The procedure is shown in Figure 8-1,Figure 8-4,Figure 8-3 and Figure 8-2.

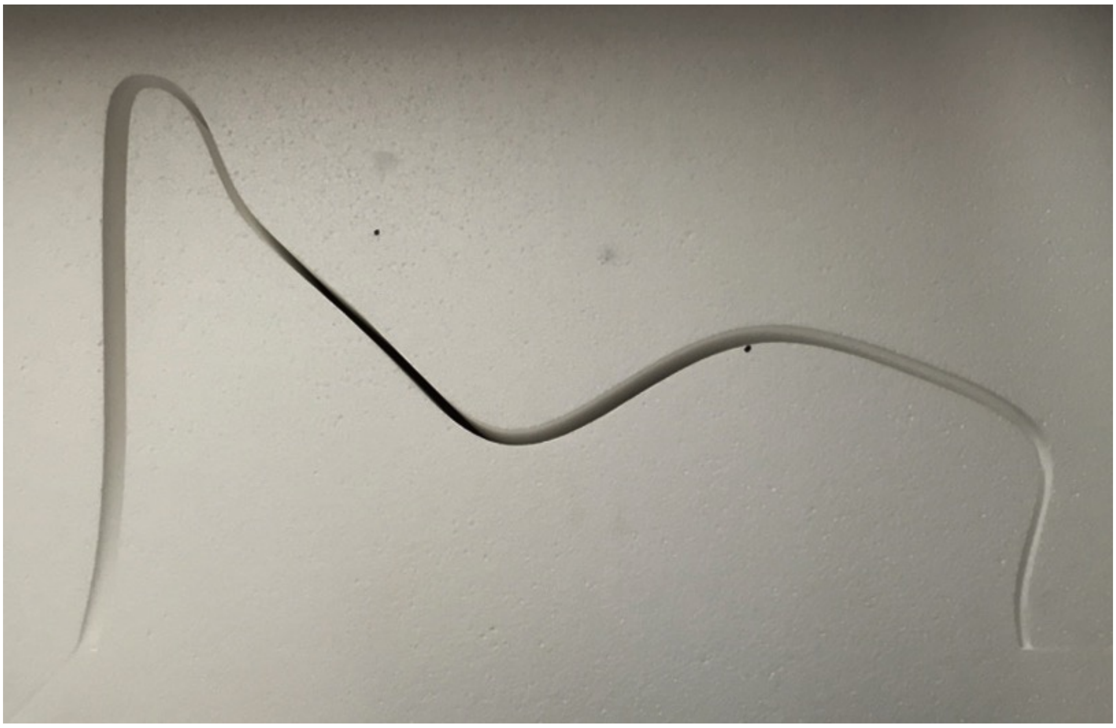


Figure 8-1. Foam formwork. (Photo: Ellen Simonsson)

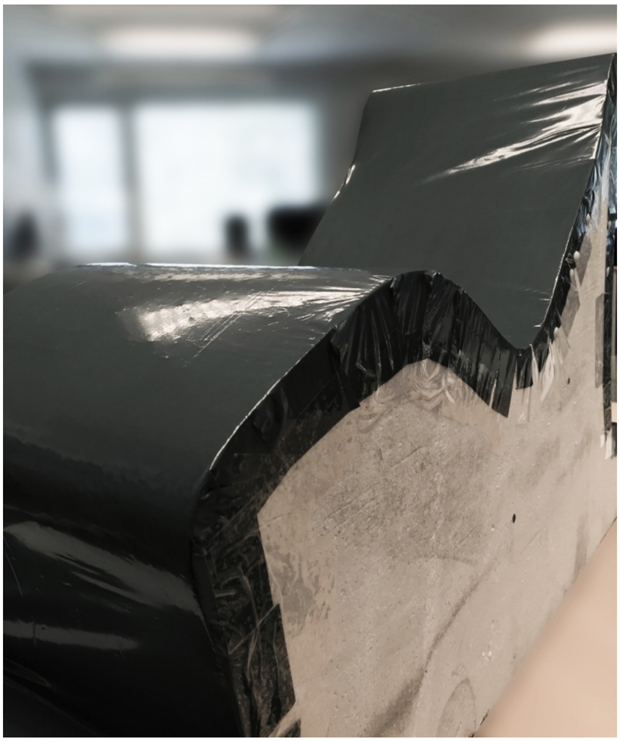
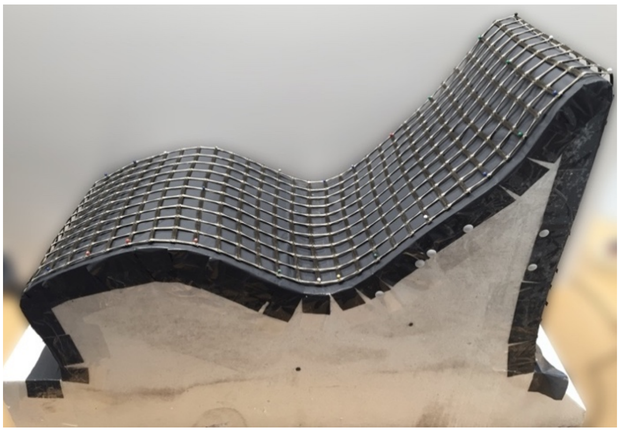
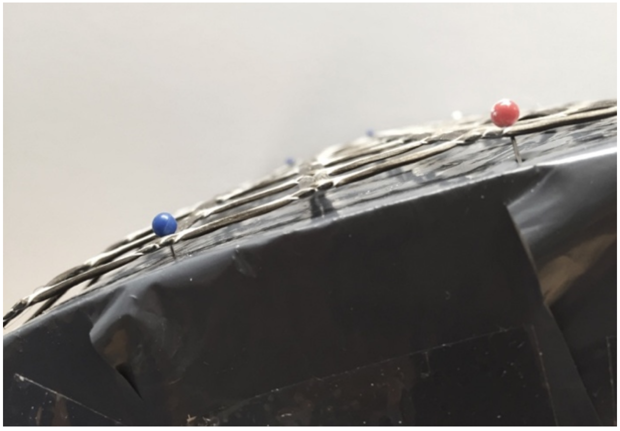


Figure 8-4. To left: Foam formwork with a layer of plastic. (Photo Ellen Simonsson).

Figure 8-3. Bottom to left: Reinforcement was placed on the formwork. (Photo: Ellen Simonsson).

Figure 8-2. Below: With nails the reinforcement was placed in right distance from foam formwork. (Photo: Ellen Simonsson).





8.1.2 Manufacturing

The upper and lower part of the formwork was placed together with clamps for two reasons; to ensure a totally closed form and to be able to remove the form easily without any risk of destroying the formwork or the hardened concrete structure.
The fresh concrete was poured down in the form until the whole form was filled. No plasticiser was used in the matrix, since the concrete was assumed to be fluid enough.

8.1.3 Result

When the formwork was released it was shown that the whole formwork was not totally filled with concrete, especially in the sharp curves the formwork had just been filled at the top. In Figure 8-5,Figure 8-6 andFigure 8-7 the result is shown.

Figure 8-5.Chair scale 1:2 from behind.
(Photo: Ellen Simonsson)

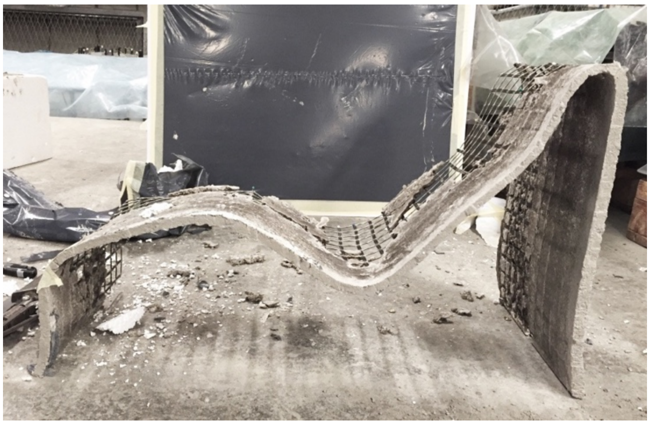


Figure 8-6. Chair scale 1:2 from side.
(Photo: Ellen Simonsson)

Figure 8-7. Detail showing how the concrete did not envelop the reinforcement. (Photo: Ellen Simonsson)

8.2 The Dome

8.2.1 Theory and method

The hand lay-up method was used for *The Dome* which was a similar manufacturing procedure as for the initial small plaster model.

The formwork was made of wood. The form was created in Grasshopper and 18 pieces of 3 mm plywood were printed in a laser cutter. The pieces were then put together, resulting in the same shape as the dome, see Figure 8-8.

Two layers of aluminium net were applied on the form to decrease the grid pattern in the finished concrete structure, see Figure 8-9.

A layer of plastic was applied over the net for two main reasons; to create a dense surface and to ensure that the concrete structure, when hardened, should be able to release from the formwork. It was assumed that no extra layer of gel was needed since the plastic was smooth enough.

Due to the fact that the reinforcement in the structure should work in two different directions, and when the circumference was changing with the height, the reinforcement was cut in one yarn pieces with different length. In order to make the manufacturing procedure smooth, the reinforcements were measured, cut and numbered before manufacturing. In Figure 8-10, the placement of the vertical reinforcement is shown.

Figure 8-8. Wood form work. (Photo: Ellen Simonsson)

Figure 8-9. Aluminum net applied over the wood form. (Photo: Ellen Simonsson)

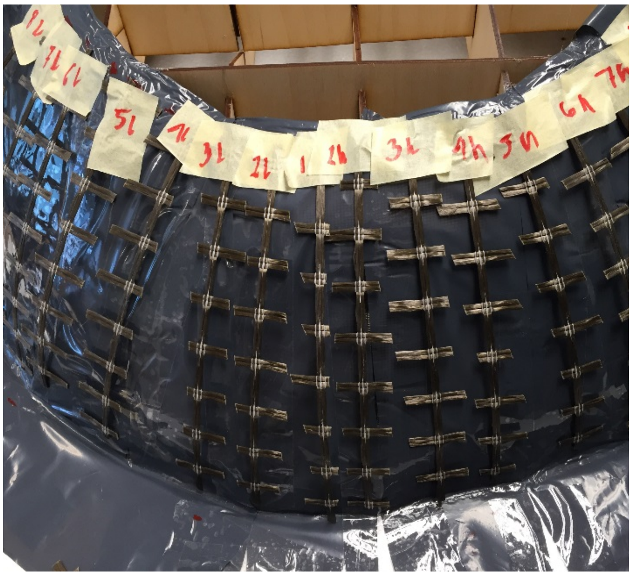


Figure 8-10. Reinforcement was placed and cut to fit the structure before manufacturing. (Photo: Ellen Simonsson)

8.2.2 Manufacturing

One layer of concrete was applied at the whole surface. The horizontal reinforcement was applied on the concrete, see Figure 8-11, and further, the reinforcement in the vertical direction. Finally, one more layer of concrete was applied, see Figure 8-12.

Figure 8-11. Horizontal reinforcement placed over one layer of concrete. (Photo: Ellen Simonsson)

Figure 8-12. Finished manufactured structure. (Photo: Ellen Simonsson)

8.2.3 Result

The outer surface become as expected, but the inside reflected the grid pattern in the formwork more than expected. The outer surface become rough and the inner surface smooth.
The thickness of the cross section varied, the thickness was thicker at the bottom than at the top due. In Figure 8-15,Figure 8-14Figure 8-13, the result is shown.

Figure 8-15.Top left: Inner surface. (Photo: Ellen Simonsson)

Figure 8-14. Top right: rough outer surface. (Photo: Ellen Simonsson)

Figure 8-13. Left: The dome. (Photo: Ellen Simonsson)

8.3 The Sculpture 1:2

8.3.1 Theory and method

The Sculpture was produced by using a combination between hand lay-up- and pultrusion method, where the textile act as both reinforcement and formwork. First, two layers of textile were overlapped, Figure 8-16, and shaped such that desired form could be created Figure 8-17. Further, concrete was applied on both side of the reinforcement structure.

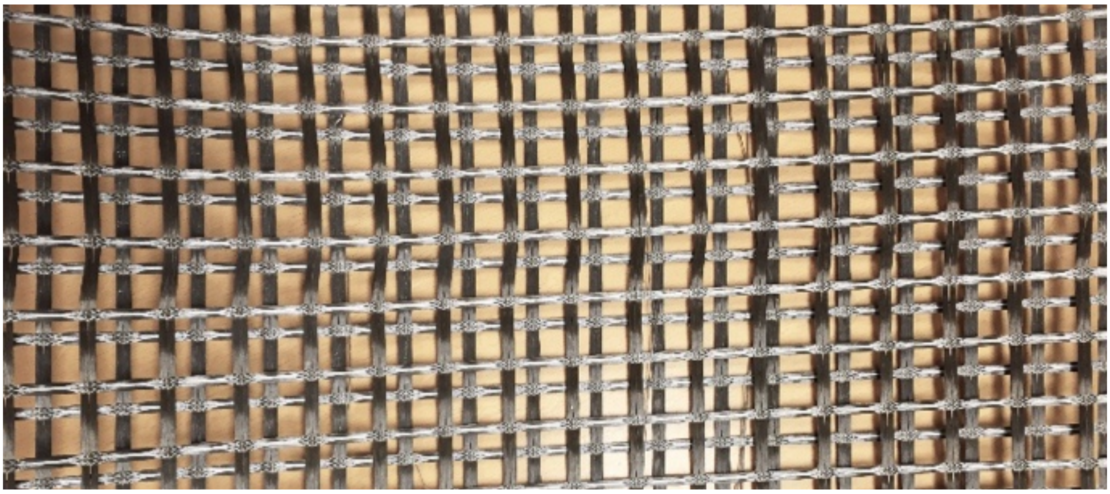


Figure 8-16.Two layer of reinforcement to create smaller holes in the open structure. (Photo: Ellen Simonsson)

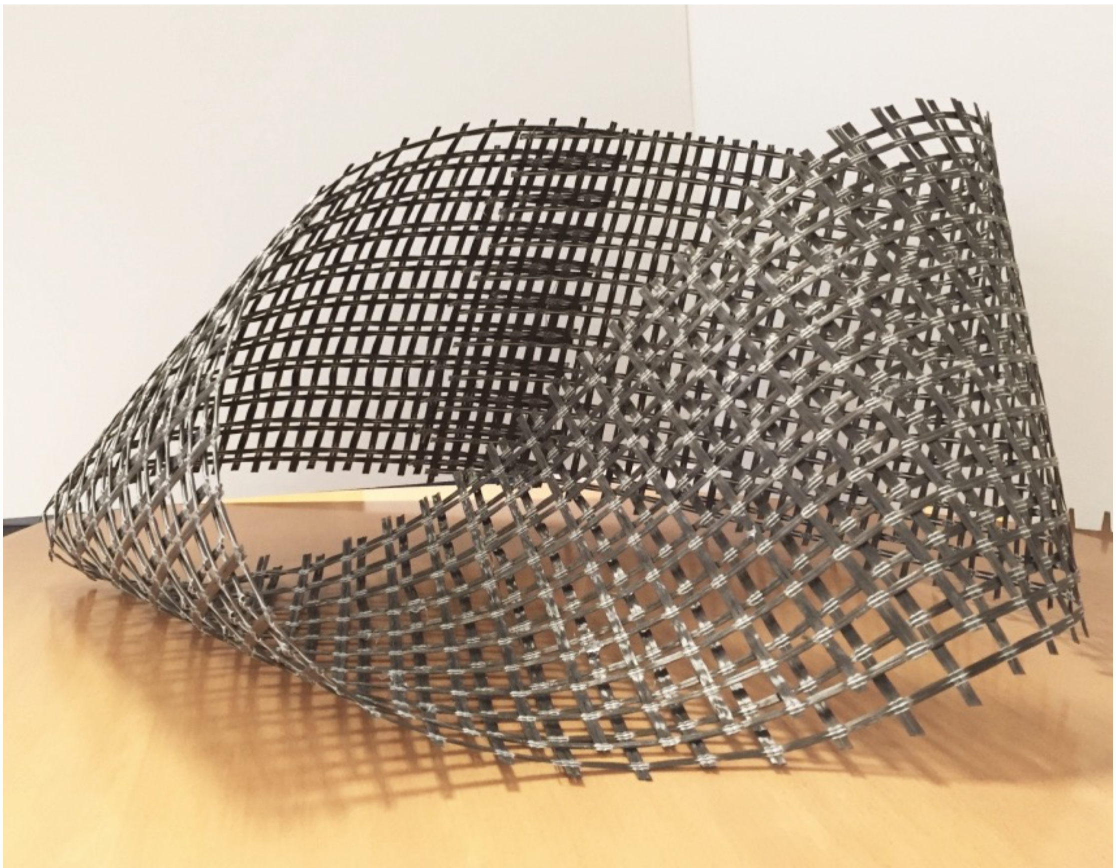


Figure 8-17. Form of reinforcement. (Photo: Ellen Simonsson)

8.3.2 Manufacturing

Two models were manufactured in two different sizes. The first model was produced in scale 1:2. There were some difficulties with the form when the concrete was applied since the self-weight became much higher. The reinforcement could not carry this extra load which led to deformation and difficulties of production. A smaller model with two stabilizers were created to overcome this problem, and the manufacturing became easier. Figure 8-19 and Figure 8-18 show the manufacturing procedure of the smaller model.

Figure 8-19. During manufacturing. (Photo: Johanna Riad)

Figure 8-18. Apply concrete on the reinforcement (Photo: Johanna Riad)

8.3.3 Result

The assumption that the reinforcement could work as the formwork was not correct. The reinforcement could not carry the bending force that the structure was affected with during manufacturing. The finishing of the structure was not aesthetical and the final shape did not have the aimed shape, see Figure 8-21 andFigure 8-20.

Figure 8-21. Sculpture. (Photo: Ellen Simonsson)

Figure 8-20. Surface. (Photo. Ellen Simonsson)

8.4 Discussion

In order to evaluate the models, the results from the manufacturing were summarised and discussed. In this sub-chapter, this process is explained. The discussion includes formwork, concrete, complexity of manufacturing and appearance of structure. It was also discussed different solutions to manufacturing problems and how to upgrade the structure.

8.4.1 The Chair

Big parts of the procedure turned out as expected, but some difficulties showed up during manufacturing. Due to the fact that the form was thin and sharp curved it was difficult to ensure that the whole formwork was filled with concrete. This problem was assumed to be solved by increasing the cross section and to use concrete with plasticiser.

8.4.2 The Dome

The assumption which was made in Chapter 6, that the reinforcement would be easy to place in right direction was correct. The reinforcement was simply placed in both directions, and stacked to the first layer of concrete during the procedure.

With the lamination method it was easy to cast the shape but difficult to create an exact consistent cross section, and the outer surface became quite rough. The surface could be smoother if extra work had been done just before hardening.

This method was time consuming and the fresh concrete changed properties during the procedure which also contributed to the rough surface.

Other solutions of manufacturing and formwork could have been used. To avoid the rough outer surface a better solution should have been to use a formwork surrounding the form, such that the structure could have been manufactured in the same manner as *The Chair*. Using this method, the fresh concrete could have been more fluid which would be preferable for the mechanical properties.

When deciding the design of the formwork, different methods were discussed. The dome could have been created by fabric and air pressure, creating the form like a balloon or as a foam sphere similar as used in the smaller model. The dome could also have been built up of sand or aggregates. The wood formwork was chosen due to its simplicity and the stable structure the grid pattern creates, and the formwork behaved as expected. But if other scales and if the designer wants the inner surface to be uniform another solution might be more preferable.

Another result from this investigation; it is believed, thanks to the consistent of the concrete and the easy way to applicate the reinforcement, that the lamination method and textile reinforcement could be appropriate when repairing existing concrete structures.

8.4.3 The Sculpture

The basalt textile had the expected behaviour i.e. the material was easily bent and twisted. Twisting the fabric led to small changes in the directions of the yarns which have to be taken into consideration, decreasing the total strength of the reinforcement.

The manufacturing did not turn out as expected. The reinforcement as formwork was not stable enough and the time for the concrete to harden was too long. From the conceptual model of the manufacturing, plaster was used which dried a lot quicker and was therefore also easier to manufacture. It is still believed that the method could have been successful if the reinforcement form should have been fixed in a certain place such that no deformation of the form could have happened when applying the concrete. Also, to use shotcrete instead of normal concrete could have improved the result.

An alternative way of manufacture could have been to first use the pultrusion method to produce a flat sheet and when it had hardened enough if would be possible to shape it into the desirable form.

The consistence of the concrete was one of the main importance of the result. The most preferable fresh concrete should have a fluid consistence, yet hard enough to stick to the reinforcements even though the form is turned around during manufacturing. These properties can be created by adding an admixture for set and hardening acceleration in the mixture.

8.5 Evaluation

The evaluation was made with the aim to choose one model to continue develop. The result and conclusion from the digital models and manufacturing procedure together with the concept and design criterion, one model was chosen.

The structures were evaluated according to several aspects, with no priority order, listed below:

- **Manufacturing**
  Difficulties and opportunities which were stated during the manufacturing
- **Formwork**
  How to construct the formwork, and how well it performed during manufacturing
- **Model**
  The result of the model based on appearance and possible opportunities of improvement.
- **How the structure highlight a new field of structural concrete art**
  With the concept as a basis, the structure shall highlight innovative application of concrete
- **Interesting for further development**
  What kind of development can be made to improve the structure’s purpose and design

Manufacturing

The Chair: During the manufacturing there were some difficulties to pour the concrete in the very thin formwork and difficult to ensure that the whole structure was filled. The fresh concrete has to be more fluid and self-compacting. The aggregates size is also of main importance when the thickness of the cross section is thin. These changes were assumed to be easy to adjust for the final model.

The Dome: With the lamination method it was easy to have control over the procedure, but also difficult to ensure a consistent thickness of the concrete layer. The reinforcement was easily placed.

The Sculpture: The combination between the lamination and pultrution method worked not well for this shape. The fresh concrete properties could have been improved by adding an admixture for improving set, fluid and hardening accelerating, to have a more fluid concrete but still able to stick to the form.

Formwork

The Chair: The formwork was done before casting, i.e. no extra work regarding the form during manufacturing which was preferable. There were some difficulties to place the reinforcement in right place.

The Dome: The formwork was both stable and strong and worked perfectly for the lamination method. The formwork was easy to remove and could be used again.

The Sculpture: For this structure, the reinforcement did not work well as formwork, due to the fact it could not carry the load from the concrete's weight. In some parts of the reinforcement structure there became big bending forces such that the structure deformed. One solution for this problem could be to stabilize the structure with a 3 dimensional cube and strings, to keep the structure stable when the concrete is applied.

Model

The Chair: The form was not filled with concrete everywhere. This could be because of too thin cross section (1 cm), thick concrete consistence and the size of aggregates. The surface was very smooth and shiny, probably because of the plastic layer on top of the foam form. The reinforcement was mainly placed in right distance from the bottom, and gave an appearance at the bottom side which was not expected but quite aesthetic.

The Dome: Even though two layers of net was placed over the wood grid form, with the purpose to get a flat surface which should not reflect the grid pattern too much, the dome got a distinct pattern. The outer side become rough as expected, and could have been more smooth if the surface would have been smoothed just before hardening.

The Sculpture: The result was as expected when the manufacturing became very challenging. The surfaces were very rough and had inconsistent cross sections, and the shape was deformed.

How the structure highlight a new field of structural concrete art

The Chair: The structure's thin and curved appearance highlights the material and from the computational model it was also assumed to be strong. The reinforcement was very easy to handle and form into right shape which also shows the advantages with this type of reinforcement.

The Dome: The dome is a structure which has been built in concrete for centuries, so in that manner this structure is not new and unique for TRC. The cross section could however be very thin and it was easy to manufacture when the reinforcement was easily placed in different directions and forms. For this structure it is more the manufacturing procedure that shows the advantages with TRC then the structure itself.

The Sculpture: If a more controlled manufacturing procedure could have been made the structure could have shown the width of applications and use of TRC. The structure had an interesting and difficult shape which would be very difficult to create with ordinary reinforcement.

Interesting for further development

The Chair: The structure was assumed to have several development opportunities. The form could be changed to be optimized both regarding mechanical behaviour and the purpose. The cross section could vary to give the chair a more dynamic and smooth appearance.

The Dome: The structure had some opportunities of development, but it was assumed that no development would give the structure a more interesting appearance or highlight TRC.

The Sculpture: The structure had an interesting form which was dependent on the manufacturing, then the form changed in shape. It was assumed that if the manufacturing procedure became more exact and organized, the structure could have several development opportunities.

In order to do a fair evaluation no ranking system was used. Instead spider web diagrams were made with five axes for each aspects described. For the three models each aspect was judged and depending on the result a point was placed at the axis. If the point was placed closer to the centre, the aspect for the model had a low value. i.e. not good, and if the point was placed towards the pentagon it indicates a high value.

From these points an area was drawn which was compared to the other models. This was the basis of the evaluation, but also, a discussion if and how the diagrams illustrate the reality was made.

Diagram 8.1. Evaluation for The Chair

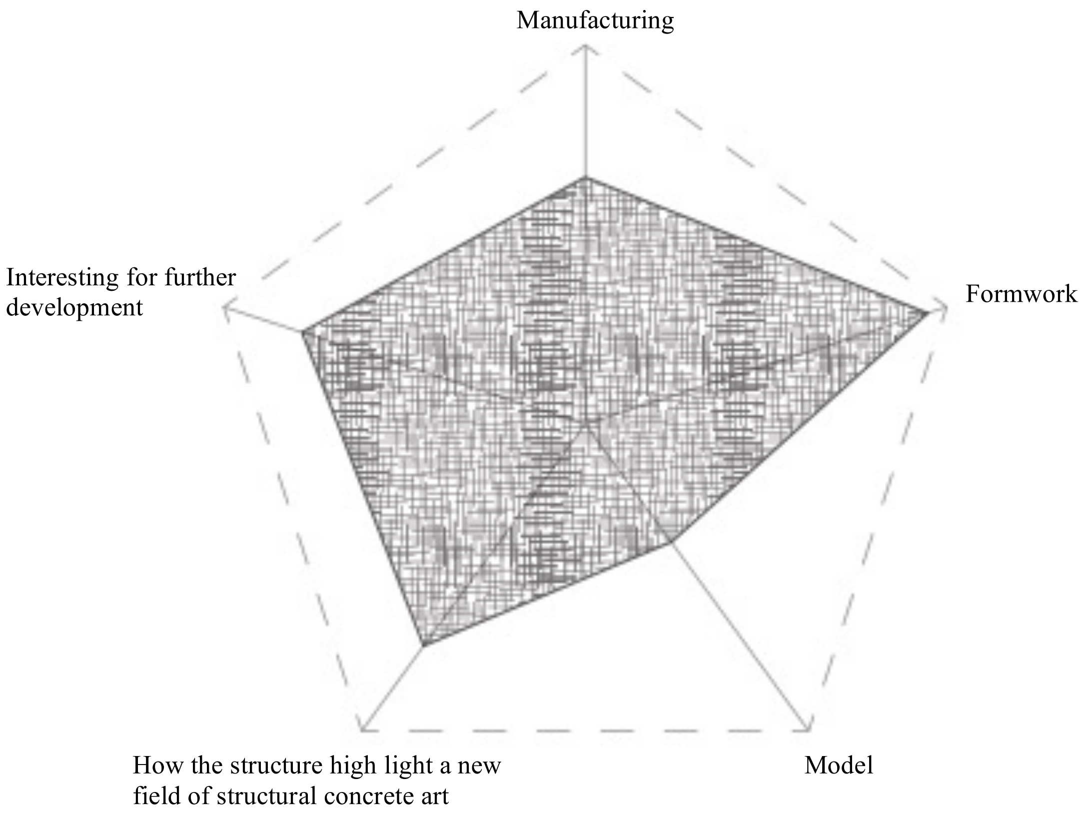


Diagram 8.2. Evaluation The Dome

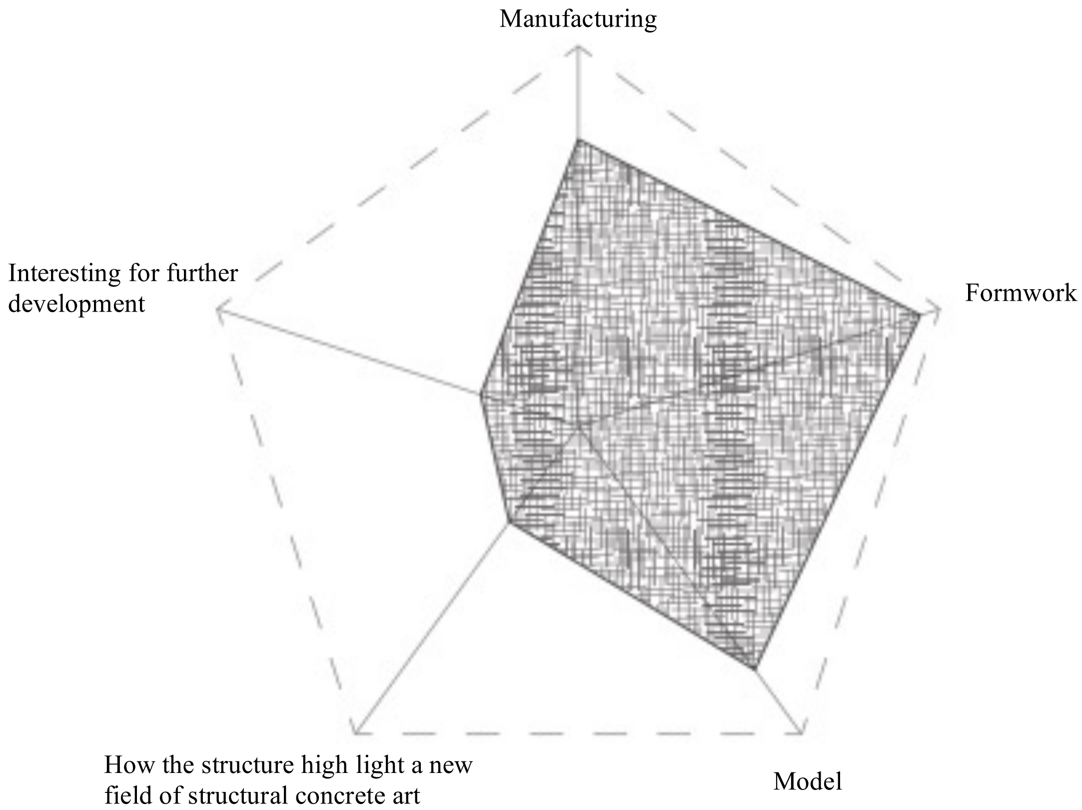
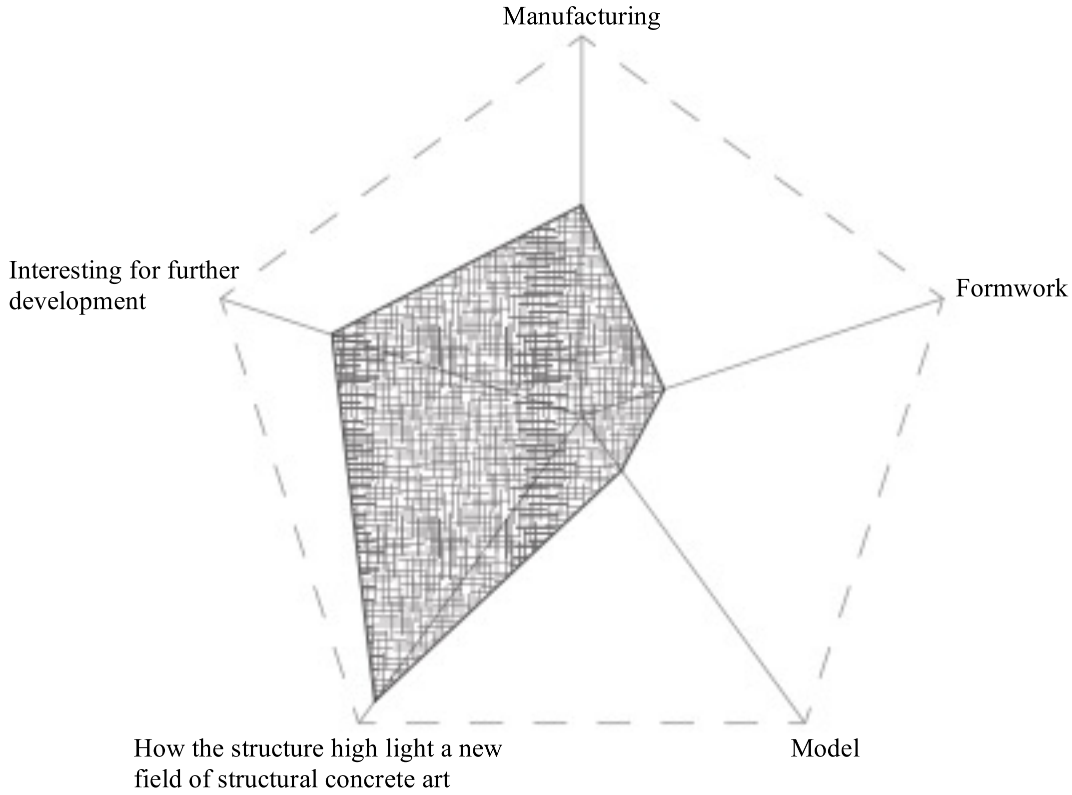


Diagram 8.3. Evaluation The Sculpture.



From the result from the investigation and the assumption for development of the structures, one structure was chosen for further development. The chair had high results on four aspects and the fifth aspect, the model, was assumed to be better if the fresh concrete would have had other properties and if the thickness of the cross section was increased. These changes were expected to be able to change for the final model. Due to this and to its form that fulfils the concept, the chair was chosen to be improved and to be manufactured in scale 1:1.

9 Final Model

The chair was chosen from the evaluation to be developed and manufactured in full scale. The computational model was improved, and the structure was estimated in ultimate limit state (ULS) and service limit state (SLS) to find critical loads. The aim for the manufacturing was to investigate the technique and if the structure would respond in the same manner to mechanical loads as estimated.

9.1 Developed form

The structure was improved regarding the concept, purpose and the structural behaviour. The dimensions were changed in order to improve the comfort and to suit persons with greater leg and back length. The thickness of the cross section was also changed in order to optimize the structure and to improve and strengthen the concept. The cross section varied from 2.0 to 2.5 centimetre along the structure. This change led to a slenderer structure with a lighter appearance and reduced weight. In order to decrease the weight even more the width of the structure was decreased. In Figure 9-6 the final design with dimensions are shown.

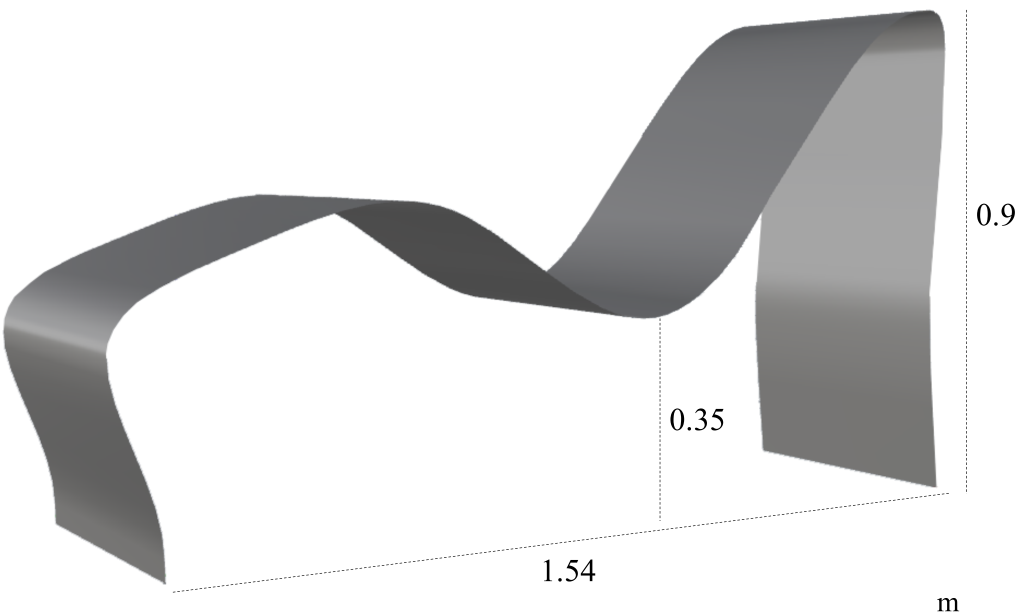


Figure 9-1. Final digital shape.

9.2 Digital Analyse

The analysis was made in following steps with an imposed load of 90 kg, (weight of sitting person)

- *Ultimate Limit State, ULS* – to estimate critical load, i.e. when the structure collapse, and to design the amount of yarns and cross section thickness.
- *Service limit state, SLS* - to estimate load for the first crack in structure

The estimated load of first crack and the failure load shall later be compared with values from the mechanical test.

9.2.1 Ultimate Limit State (ULS)

The load combination (load case 2 from Chapter 7.2.2) was estimated as following:

$$Q = \sum_{0}^{l} 1.35G + \sum_{\text{bottom}} 1.5P_{\text{tot}} \tag{9.1}$$

Where

G = self weight [N]

P_{tot} = total weight of person [N]

To estimate the design moment equation 9.2 and 9.3 where used

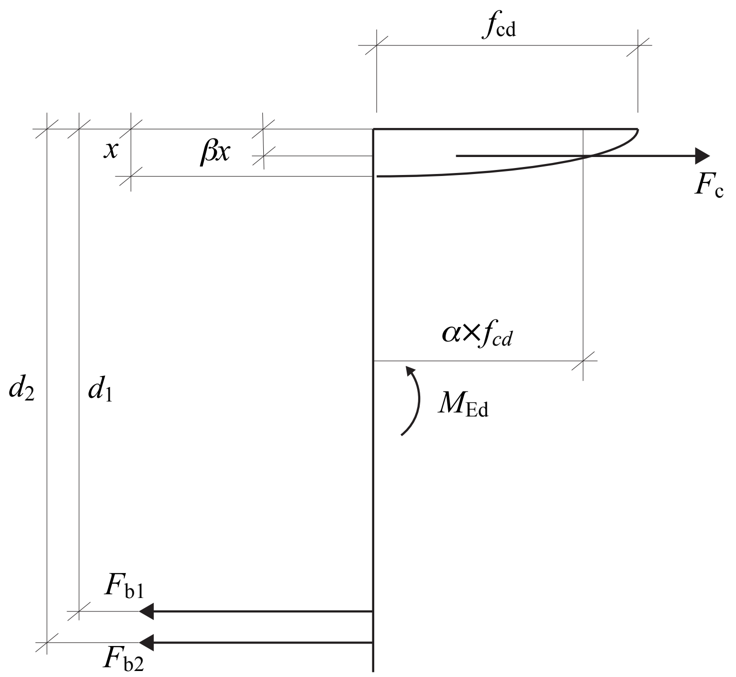


Figure 9-2. Stress distribution according to the working curve of concrete.

$$\alpha \times f_{\text{cd}} \times b \times x = f_b \longrightarrow x \tag{9.2}$$

Two layers of reinforcement were chosen.

$$M_{\text{Rd}} = F_{\text{b1}} \times (d_1 - \beta x) + F_{\text{b2}}(d_2 - \beta x) \tag{9.3}$$

Changes were made in shape and cross section thickness such that following expression should be fulfilled in every cross section

$$M_{\text{Rd}} \geq M_{\text{Ed}} \tag{9.4}$$

To optimize the thickness according to moment capacity the moment capacity for three different cross section where estimated. In equation 9.4 the result of the utilization ratio for cross section where the maximum moment occurred shown.

$$\frac{M_{\text{Rd}}}{M_{\text{Ed}}} = 1.28 \geq 1.0 \tag{9.5}$$

The failure load occurs when the dimensioned moment become greater than the design moment.

$$M_{\text{Ed}} \geq M_{\text{Rd}} \tag{9.6}$$

9.2.2 Crack load, SLS

The load, in service limit state, when the first crack occur was estimated from the tension capacity of concrete. This value was compared to the maximum tensile stress in the structure.

$$\sigma_{\text{c}} \leq f_{\text{ct,fl}} \text{ , no cracks} \tag{9.14}$$

Where:

$$f_{\text{ct,fl}} = k \times f_{\text{ctm}} \tag{9.15}$$

$$k = 1.6 - h \tag{9.16}$$

The first crack will occur when

$$\sigma_{\text{c}} \geq f_{\text{ct,fl}} \tag{9.17}$$

The load which responded to this stress was found in Karamba.

9.2.3 Result of Analysis

The cross section design for the most critical element is shown in Figure 9-3. The thickness of the section is varying along the side but the distance between the reinforcement and the bottom will remain.

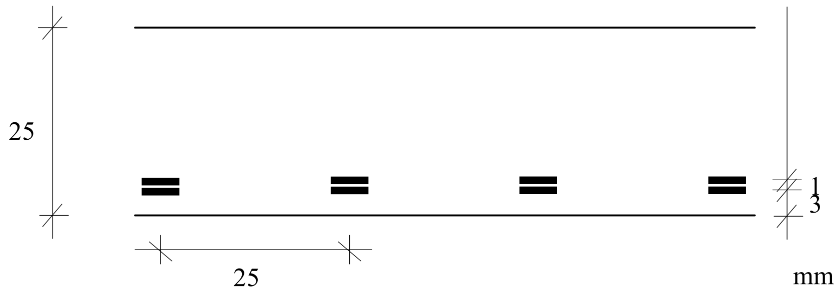


Figure 9-3. Cross section design where the greatest value of moment occurred scale 1:1

Table 9.1 The results of the final shape

Maximum moment in structure (ULS)	604 Nm
Maximum tensile stress in structure (ULS)	11.7 MPa
Cross section thickness	Varies from 2 to 2.5 cm
Weight	91 kg
Numbers of yarns	20 yarns in two layers

9.3 Manufacturing

In order to test the manufacturing process in 1:1 scale and investigate if the estimated load calculations were accurate, two final models were manufactured. One model that would be tested in bending to find critical loads, and another to work as a show-example. Unfortunately, the manufacturing went not as expected and therefore, also a third model was made.

9.3.1 Formwork

The formwork was made with the same method as for the small-scale-formwork. Due to its greater scale it was necessary to divide the structure into two parts; the back and the leg. These two parts were created by a foam cutter and glued together. The formwork was enveloped by tape. The tape had a smooth surface, and it was assumed that this was adequate to remove the formwork after the concrete had harden. Two layers of reinforcement were then applied approximately 3 mm from the bottom with nails.

The bottom part, before the formwork was put together is shown in Figure 9-4.

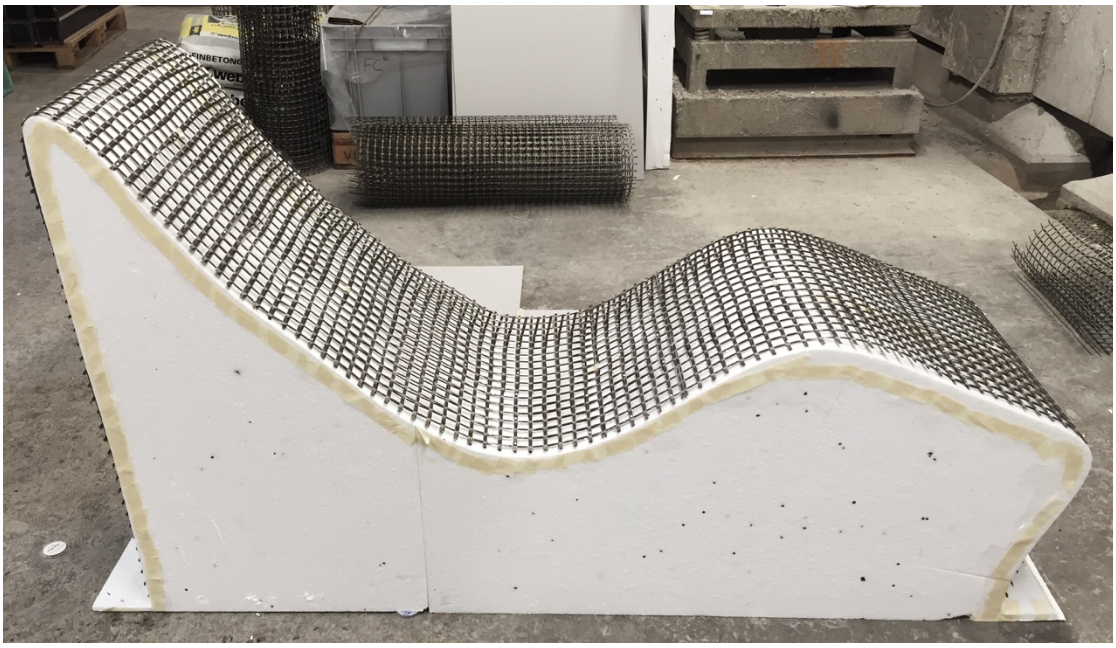


Figure 9-4. Bottom part of the formwork with a layer of tape and two layer of reinforcement. (Photo: Ellen Simonsson)

9.3.2 Casting

The concrete which was used was assumed to have similar properties as PZ-0899-01 in both harden and fresh state, with the same strength capacity and same w/c –ratio. The biggest aggregate size was 6 mm, bigger than in PZ-0899-01. It was assumed that this should not affect the manufacturing and the result since it still was much smaller than the open structure in the reinforcement i.e. it should be able to envelop the reinforcement. Three cubes were also casted, to be able to test the concrete compressive strength.

The first casting procedure was made in two different stages. The model which was aimed to be tested in bending and the three cubes were casted first. From this casting process it was found that:

- The fresh concrete, even though plasticiser was used (1% of binder), was still not fluid enough.
- The formwork was not stable enough. The pressure from the concrete become too high and the formwork started to deform.

In Figure 9-6 the deformed shape is seen, and in Figure 9-5 it is shown that the concrete was not fluid enough and did not envelop the reinforcement.

Figure 9-6. Some parts of the structure became twice as wide as expected. (Photo: Ellen Simonsson)

Figure 9-5. Not all reinforcement was enveloped by the concrete. (Photo: Ellen Simonsson)

For the second casting, the problems shown from the first casting were solved by increasing the w/c-ratio and by stabilizing the formwork with extra walls surrounding the form and with straps to ensure that the formwork would not be affected by the compression force from the concrete. The improvement of the formwork can be seen in Figure 9-7 and Figure 9-8.

Figure 9-7. Formwork with 1 cm MDF to stabilize the form. (Photo: Ellen Simonsson)

Figure 9-8. Clamps to stabilize the formwork. (Photo: Ellen Simonsson)

When casting the second model, the consistence of the concrete was good and it was easy to fill the formwork. But still, the formwork was not stable enough and some parts become wider and some thinner. This is shown in Figure 9-10 and Figure 9-9. The casting procedure was forced to be discontinued when the formwork deformed too much.

Figure 9-10. Deformation of formwork causing thinner parts. (Photo: Ellen Simonsson)

Figure 9-9. Deformation of formwork causing wider parts. (Photo: Ellen Simonsson)

From this investigation it was discussed how to make the formwork stable enough when the force from the fresh concrete starting to push the form. One way which was discussed was to create walls of studs and MDF-plates which should be nailed into a plywood or MDF plate, see Figure 9-11. It was assumed that with this technique, the walls whould resist the forces and the formwork should be hold in place.

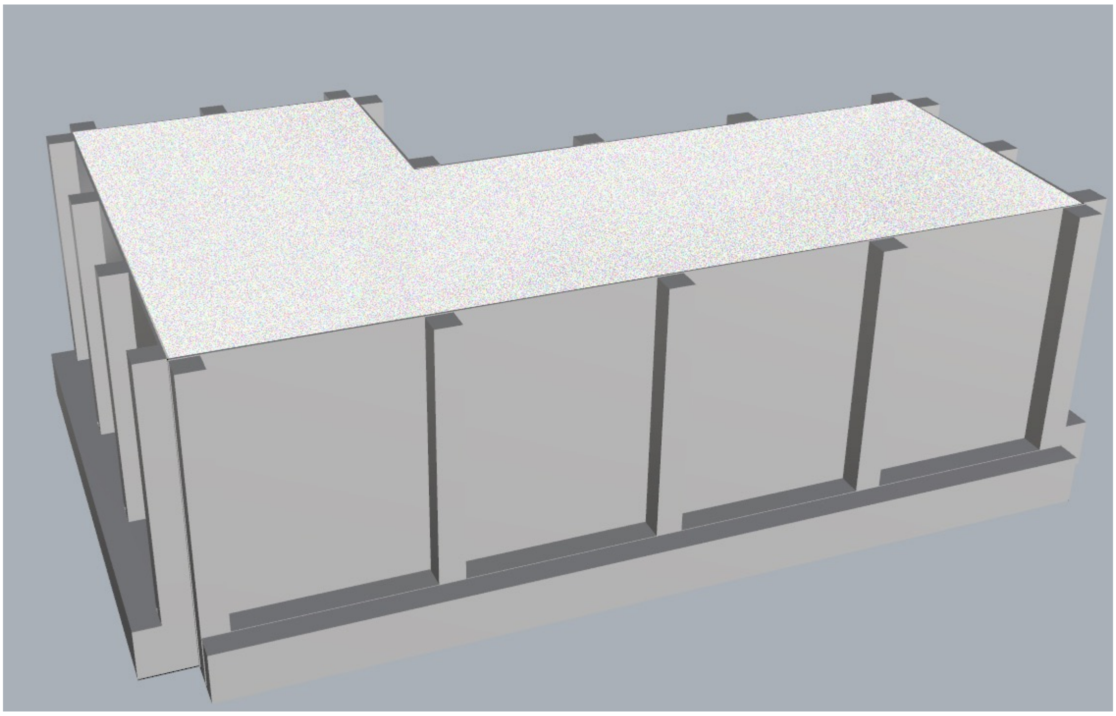


Figure 9-11. Illustration of stabilizing walls.

The final formwork with stabilizing walls is seen in Figure 9-12.

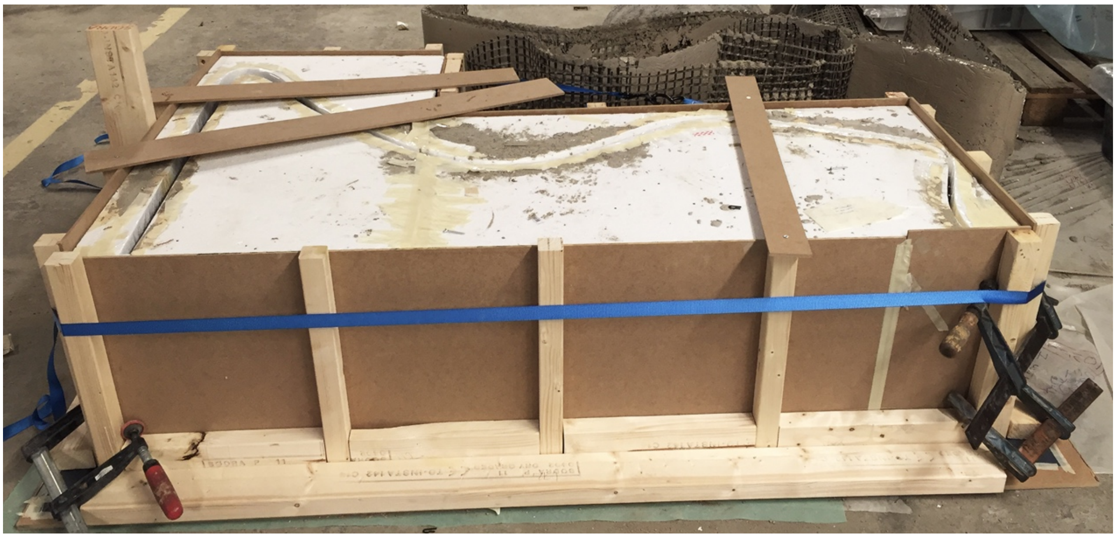


Figure 9-12. Formwork with stabilizing walls. (Photo: Ellen Simonsson)

Even though the stabilizing system was added to the formwork some deformations occurred during manufacturing. When the formwork was removed it was shown that there were some parts of the structure that was not enveloped by concrete, in Figure 9-13 the third model is shown.

Figure 9-13. Third model. (Photo: Ellen Simonsson)

Neither of the structures were sufficiently good for mechanical load testing. Due to this, the failure load and first-crack load could not be verified.

10 Result

The objectives of this thesis were to:

- Investigate structural behaviour of complex forms of textile reinforced concrete.
- Investigate suitable design and different ways to design structures with textile reinforced concrete.
- Investigate appropriate manufacturing techniques.

With these objectives the question "*If TRC can be a suitable material for structures with complex shapes?*" was explored.

From investigations, based on theory and practical work described in the report, the results are:

Structural Behaviour

From theory it was found that TRC has a high strength capacity which varies depending on concrete matrix, reinforcement material and design, and the manufacturing procedure. The reason of why the strength capacity decreases for AR-glass and basalt fibres when casted into concrete, is probably due to chemical reactions and solutions need to be investigated further.

From the computational models the shapes were investigated, which showed that even small changes could change the stresses and moment within the structures.

One of the aim for the final structure was to test it for mechanical loads, but due to manufacturing difficulties, the structure couldn't be tested and therefore the computational model was not verified. From this thesis no result of the final structural behaviour could be determined, and therefore it is unclear how the reinforcement was affected by the bending and twisting during manufacturing.

Design

The investigated design methods; *Form-finding, simple mathematical geometry* and *free form* are all suitable for TRC-structures if appropriate materials and software are used. By working with representations of material in smaller scale, shapes and structures could be created from the materials behaviour and properties.

Manufacturing

The most promising manufacturing technique is dependent on shape, purpose and aesthetic. The result showed different advantages and disadvantages that need to be considered and developed from case to case.

A great advantage during the manufacturing of the chair was that the reinforcement was easily placed and formed into right shape, but a disadvantages was to place the reinforcement in the exact distance from the surface. With a cross section of just 25 mm the precision is very important.

To ensure this, appropriate spacers need to be created. The most important properties these spacers should have are:

- Be able to stick in the form – without being too visible in the surface.
- Be able to loosen from the form – when the form is removed from the structure.
- Be able to hold the reinforcement – lock the reinforcement in a certain place and distance from the surface.

To be able to cast thin structures, as the chair, a very fluid concrete consistence was needed which could not just be created with plasticizer but also with reduced w/c-ratio. This will result in a reduced concrete strength which need to be highly considered during the design process.

With these investigations and due to the method, where both theoretical and practical analysis were used, it was shown that TRC can be a suitable material for more complex structural shapes, but manufacturing methods need to be further developed.

11 Discussion

Structural Behaviour

Due to difficulties with the manufacturing, the computational model was not verified. The result should have been verified in another FE-analyse program to get an accuracy in the calculation. For example, Karamba applies Kirchoff's theory. i.e. no shear forces are included, which would be interesting to see how these forces would affect the structure. The analysis of the structural behaviour is therefore just theoretical and the accuracy of the measurement would have been more significant if physical bending test would have been performed. In the design process, a mechanical bending test should have been done earlier for the small models in Chapter 8 to verify the FE-program and to have the structural behaviour as an evaluation aspect.

Design and Method

The material which were chosen to represent TRC in a smaller scale were suitable, but before chosen the three most promising models in Chapter 6, textile reinforcement and concrete should have been tried out for the structures. If this was done, difficulties with manufacturing would have been addressed and maybe also other models would have been chosen.

Even though the final design of the chair had a clear purpose which displayed the application of TRC and the concept well, improvement of the shape could have been done by designing a double curvature at the leg, bottom and back part. This improvement would have increased the strength and also the comfort of the structure.

Manufacturing

The manufacturing needs to be considered early in the design process. What method to use and how to create the formwork. From this investigation it was found that the formwork needs to be very stable when the concrete pressure becomes very high and can destroyed the formwork. TRC is a material which can be used in a wide range of structures and shapes, but how to create it has more limitations. Therefore, if would have been good if a conceptual manufacturing would have been included in the design process.

Improvement of the result

The main improvement to strengthen my result would be to cast a final and complete structural model to test in mechanical loading and to compare the design with a steel reinforced "chair". Due to time limitations this was not made.

12 Conclusion

The objectives of the thesis were investigated in both theory and practice, and indicates that TRC is a material that can be suitable for more complex structural art if the manufacturing methods are developed. Even though not all results were complete and verified, the main outcome shows that:

- The design and application possibilities with TRC are wide.
- It is easy to work with the reinforcement in the design.
- The textile reinforcement was easily put in right direction.
- The structure with TRC can be very efficient and optimized.
- The manufacturing method for complex shapes need to be considered and tried during the design process.

With this outcome, it was stated that TRC is a suitable material for more complex shapes and forms, and that it can highlight new types of structural art.

Following, a conclusion over the method is described:

Process

The way of working with an iterative process in both theory and practice was a good method when exploring new material and form, mainly when the result and finished structure is not known from the start. This method raised questions and solutions that would not have been seen if the process was linear and just theoretical. Also, from the smaller physical models, an initial global structural analysis could be drawn.

Models

By working with smaller physical models, with material that represents TRC, the understanding of shape and structural form with the material became improved. The conclusion that both *free form* and *form-finding method* are great tools when designing TRC structures was made from this step in the process. The materials which were used represented TRC well and it worked to form different shapes in several ways that conclusions could be drawn from.

It would have been good it the real materials had been used earlier in the design process, when problems regarding weight, stiffness and manufacturing could have been addressed.

Optimization

In the computational model the shapes were optimized according to stresses and maximum moment within the structure. Depending on purpose, the models were computed in different ways with different in data and outcome. This development could have been better if the structures had a more specific load case and a certain goal for the improvements.

Manufacturing

An appropriate production method is depending on factors such as; economy, purpose, manufacturing procedure, location and shape of the structure. For all structures, the manufacturing method needs to be reflected in early states of the design process, to know if there is any limitations or demands which need to be considered. It was found in the thesis that the manufacturing and creating a suitable formwork was the most difficult in the process, and is therefore recommended to be addressed early in the design phase.

The result from the combination of lamination- and putrusion method when manufacturing *The Sculpture* showed difficulties but parts of it indicates that it can be an appropriate manufacturing method. If the reinforcement would have been stable enough, such that it did not deform when the concrete was applied, and if shotcrete would have been used, the final structure would have looked differently. But, this needs to be investigated further.

Spacers for more complex shapes and different formworks need to be developed in both shapes, sizes and for different type of reinforcement design.

One of the limitation of the thesis was to not focus on specific concrete compositions. If this would have been done, the structures may have been better, since the concrete played an important role in the manufacturing, especially the w/c-ratio and the amount of plasticizer.

12.1 Further studies

It was seen in the thesis that the textiles were easily shaped into different forms which was one of the main advantages with textile reinforcement, but the consequences of this treatment is not investigated or known. When bending the fibres, the structure of the reinforcement is disturbed and it would be interesting to know how this treatment affects the strength of the reinforcement and the composite.

The main difficulties found in the thesis was the manufacturing process in complex shapes. Both different tools, method and improvement of already existing methods needs to be investigated further.

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13.2 Figures

Figure 2-4. V.Fraas Solutions in Textile. (Photo). http://www.bft-international.com/en/artikel/bft_3D_biaxial_textile_reinforcement_1772351.html. (Accessed 2016-01-23)

Figure 2-6 Kok, M., 2013. *Textile reinforced double curved concrete elements Manufacturing free-form architecture with a flexible mould*. (Illustratition)

Figure 3-4 DistTEX. (Photo). http://www.disttex.com/english/. (Accessed 2016-01-28)

Figure 4-1 Bauko 2, RWTH Aachen University. From Scholzen, A., Chudoba, R. & Hegger, J., 2015. Thin-walled shell structures made of textile-reinforced concrete: Part I: Structural design and construction. *Structural Concrete*, 16(1), pp.106–114.

Figure 4-2 InnovationsinTextiles. (Photo). http://www.innovationintextiles.com/textile-concrete-bridge-in-albstadt-lautlingen/ (Accessed 2016-01-25)

Figure 4-3 From Williams Portal, N., 2013. *Sustainability and Flexural Behaviour of Textile Reinforced Concrete*, pp.23. Available at: http://publications.lib.chalmers.se/records/fulltext/182607/182607.pdf.

Figure 5-1 Institut fuer Leichtbau Entwerfen und Konstruieren, Universitaet Stuttgart, Bildarchiv.