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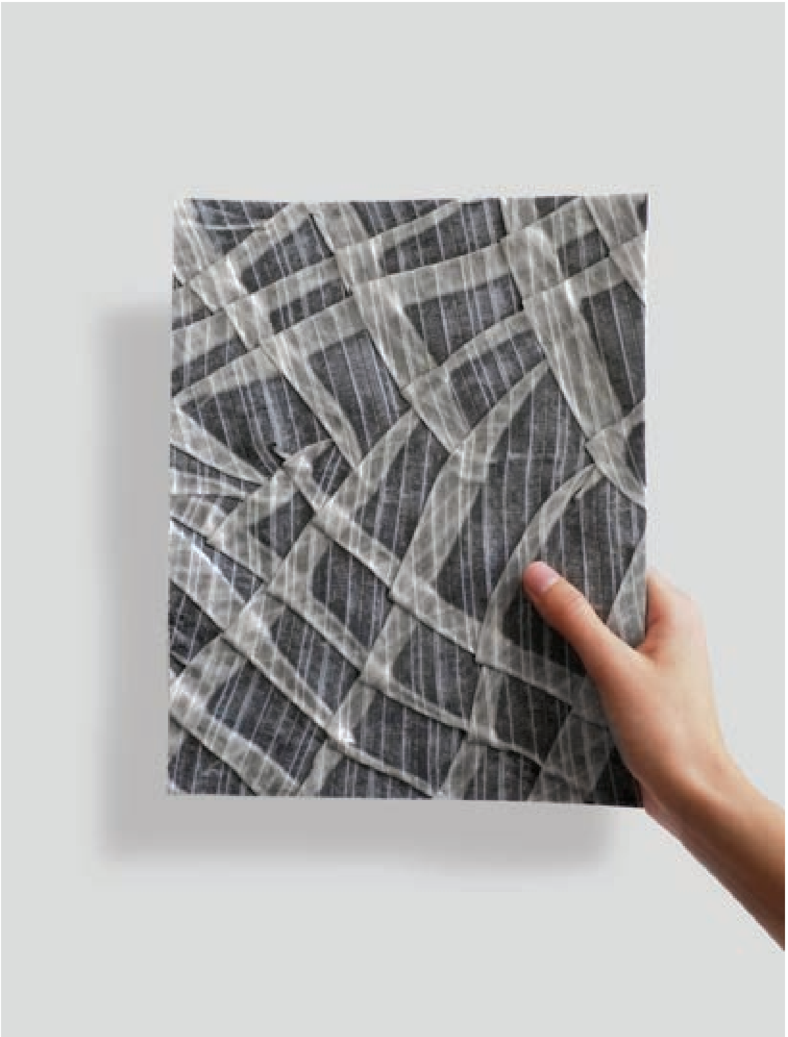

WITHIN THE SAME THREAD

STRUCTURAL AESTHETICS IN LOAD CARRYING FIBRE COMPOSITES

Master's Thesis in Structural Engineering and Building Technology

ELLEN ORDELL

Department of Applied Mechanics
Division of Material and Computational Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
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Prototype, folded composite

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ABSTRACT

Within the field of fiber composite materials, fiber orientation and distribution are the most important factors influencing a material's mechanical properties. Today, several textile and manufacturing techniques are used to orient and distribute fibres. Most common are layering, but there are also embroidery and twinning techniques. Only few applications make use of the appearance of the constituent fibers as part of the aesthetical expression of the composite.

In Within the Same Thread Ellen Ordell, architectural engineering student, and Therese Amus Gidlöf, textile design student, develops multi-fiber composite materials in various textile techniques. The thesis work aims to expand the relatively unexplored field of integrated solutions between textile design and material performance.

The work is based on the hypothesis that an iterative design and analysis process, combined with prototype manufacturing, can result in innovative variations of fiber composite materials. The prototypes are produced at SICOMP research laboratory. The project resulted in a series of composites employing textile folding techniques.

Experimental results indicate that the fold improves the bending stiffness of a fiber composite material. The sample series results in several design options for fiber composites where its textile reinforcement can appear both in a visual and tactile manner. The work also validates a computational FE-model for the suggested folding technique.

Key words: fiber composite materials, composite mechanics, interdisciplinary collaboration, Architectural Engineering, textile design, FEM, material testing

I en och samma tråd
Strukturell estetik i belastade fiberkompositmaterial
Examensarbete inom Structural Engineering & Building Technology
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Avdelningen för Material- och beräkningsmekanik
Chalmers tekniska högskola

SAMMANFATTNING

Inom fältet fiberkompositmaterial är fibrernas orientering och fördelning av stor betydelse för materialets mekaniska egenskaper. Idag finns flera textila tekniker och tillverkningstekniker som används för att orientera och distribuera fibrer. Den vanligast förekommande metoden är "layering" (lager på lager) eller olika typer av broderi och tvinning. Några få tillämpningar av fiberkompositer använder sig av de ingående fibrernas utseende som en del av formgivningen.

I *I en och samma tråd* utvecklar Ellen Ordell, arkitektur och teknikstudent, och Therese Amus Gidlöf, textildesignstudent, flera fiberkompositmaterial i olika textila tekniker. Arbetet strävar efter att vidga det relativt outforskade fältet av integrerade lösningar mellan textil design och materialegenskaper inom kompositmekanik.

Arbetet bygger på tesen att en iterativ design- och analysprocess kombinerad med tillverkning kan skapa innovativa varianter av fiberkompositmaterial. Proverna tillverkas med vacuuminjicering på Sicomps forskningslaboratorium. Arbetet resulterade i en serie av kompositprover i veckningsteknik.

Försöksresultat tyder på att veckning förbättrar böjstyvheten hos ett fiberkompositmaterial. Provserien resulterar i flera gestaltningsmöjligheter för fiberkompositmaterial där dess textila armering kan framträda både visuellt och taktilt. Arbetet validerar också en modelleringsteknik för FE-modeller för att simulera egenskaper hos veckade fiberkompositer.

Nyckelord: Kompositmaterial, kompositmekanik, fiberkomposit, tvärvetenskapligt samarbete, Arkitektur och Teknik, textildesign, FEM, materialprovning

CONTENTS

PREFACE

My background going into this thesis project is a bachelor's degree in Architectural Engineering and a Master of Architecture. This is the thesis project of master's program Structural Engineering and Building Technology. I have broadened my curriculum with the course Composite Mechanics at the Department of Applied Mechanics.

Considering my background I wanted to do this thesis integrating design and engineering focusing on textile composites. For this I wished to collaborate with textile design. Through the Swedish School of Textiles in Borås I got in touch with my partner for this project – textile designer Therese Amus Gidlöf, at the time pursuing her Bachelor's degree in Textile Design.

My supervisor Dr Mats Ander and teacher Dr Martin Fagerström put me in contact with Dr Maciej Wysocki, researcher at Swerea Sicomp. Dr Maciej Wysocki became a valued supervisor and we conducted all our tests and prototypes at Swerea Sicomp.

The project was made possible by sponsorship and grants from the foundation ARQ who promotes Swedish architectural research, Smart Textiles, a part of University of Borås, Britt-Lisa Landahls stipendiefond and TEKO, Swedish Textile and Clothing Industries Association.

I would like to extend my warmest thanks to Dr Maciej Wysocki and MSc Peter Hellström for their assistance and guidance at Sicomp, without whom this project would not have been possible. I also thank Dr Mohammad Sadegh Rouhi for his valued assistance with FE-analysis.

Finally my supervisor Dr Mats Ander has been outstanding in competence, and support, from the first day to the last. Thank you.

Göteborg, januari 2015
Ellen Ordell

1 BACKGROUND TO COMPOSITE MATERIALS

1.1 FIBRE COMPOSITE MATERIALS

Composite materials are materials that consist of two or more materials. For example are bone and wood natural composites and fiberglass-epoxy and concrete are common man made composites. Agrawal, Broutman and Chandrashekhara (2006) give the following definition: *"The word "composite" means, "consisting of two or more distinct parts". Thus a material having two or more distinct constituent materials or phases may be considered a composite material. However, we recognize materials as composites only when the constituent phases have significantly different physical properties."*

In this thesis work emphasis is on fiber-reinforced composites, as Agrawal et al defines: *"Composites consists of one or more discontinuous phases embedded in a continuous phase. The discontinuous phase is usually harder and stronger than the continuous phase and is called the "reinforcement", whereas the continuous phase is termed the matrix."*

Common composite matrix materials are epoxies and polyesters in the range of thermosetting plastics and polystyrene and nylons in thermoplastic polymers. Fibre reinforcing materials are commonly carbon fibre or glass fibre. Applications can be found in the aerospace, automotive and construction industries. Natural fibres suitable for fibre composites are for example flax, jute, sisal and hemp fibres.

1.2 PROPERTIES OF FIBRE COMPOSITE MATERIALS

The two most important properties of oriented-fibre composites are their high strength to weight ratio and controlled anisotropic behavior (Agrawal, Broutman and Chandrashekhara, 2006).

Reinforcement orientation is the most important parameter to control in order to achieve these beneficial material properties. The reinforcement properties are affected by the shape, size and size distribution of its constituent fibres. The reinforcing threads influence the material properties by their distribution and orientation. Distribution and orientation of reinforcing threads in composite materials is the focus of this thesis work.

An important characteristic for fibre composites is that the strength along the fibre direction is magnitudes larger than the strength perpendicular to the fibres. In particular this means that due to the mechanical properties of fibre composites the main fibre orientation should follow that of the principal stresses (Komposithandboken, 2006). In this thesis the focus are to control the properties of the composite material through different distribution and orientation of the reinforcing fibres with regard to the principal stress directions and magnitudes. The properties of the composite material here refer to both the structural, quantifiable properties and the aesthetic qualities.

1.3 ORIENTATION AND DISTRIBUTION OF FIBRES IN A COMPOSITE MATERIAL

Today there are several methods used for the purpose of designing orientation and distribution. Some of the more important methods are described below. The methods described have been chosen since there are examples of integration between aesthetic design and structural design. It should also be noted that these methods are closely related to manufacturing methods.

1.3.1 LAYERING

Layering is the most commonly used technique for orienting fibres in a laminate. The other techniques have layering as a base structure. A layered composite is a combination of fibres and matrix. Usually the fibres are introduced as sheets of woven or non-woven textiles. The woven textiles have one or more dominant fibre directions and the properties of the laminate are designed by orienting these directions. The number of layers and their orientation defines the lay up of the laminate. For example [0, 90, 45, 90, 0] is a laminate with five layers of textiles with the fibre orientations 0°, 90° etc. with regard to the axis defined parallel to the length of the laminate. Layering is used in several manufacturing techniques, such as vacuum injection, hand lay-up or compression molding.

There are many examples of layered composites used with transparent resin that displays the textile. These can be carbon fibre weaves displayed in sports cars or mobile phone shells. But also fiberglass has been used for example in lamps, displaying the structural fibre. Natural fibres are used both as aesthetic and structural components in a research project by Danish Technological Institute, see figure below.

Figure 001. Sample and stool prototype of natural fibre composite at the Danish Technological Institute, DTI.

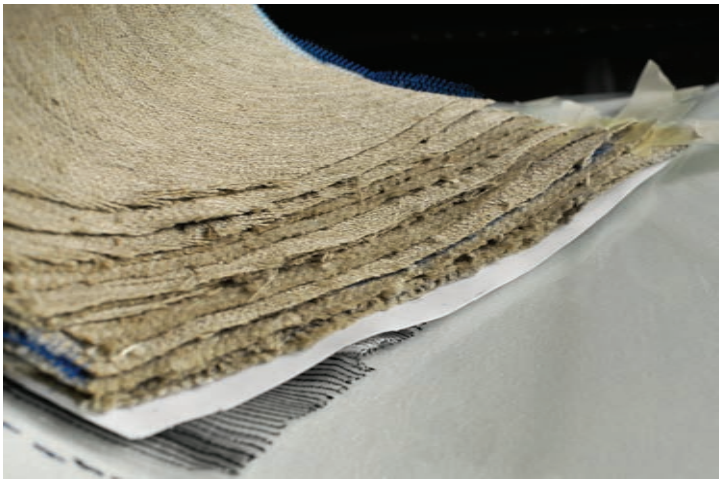


Figure 002. Layers of flax weave prior to epoxy infusion. Layers usually have different fibre directions that handle different stresses.

1.3.2 DISTRIBUTION OF FIBRES WITH EMBROIDERY TECHNIQUE

The Leibniz Institute of Polymer Research in Dresden has since the 1990's investigated the possibilities of Tailored Fibre Placement (TFP), which is a textile manufacturing process for production of preforms for composite parts with fibre layouts of arbitrary direction (A. Spickenhauer, M. Schulz, K. Gliesche, and G. Heindrich, 2008) (P. Mattheij, K. Gliesche, D. Feltin, 1998). This process utilizes a CAD-FEM-CAM approach to allow a consistent transfer of locally optimum fibre quantities and orientations into fibre preforms, using automated embroidery techniques.

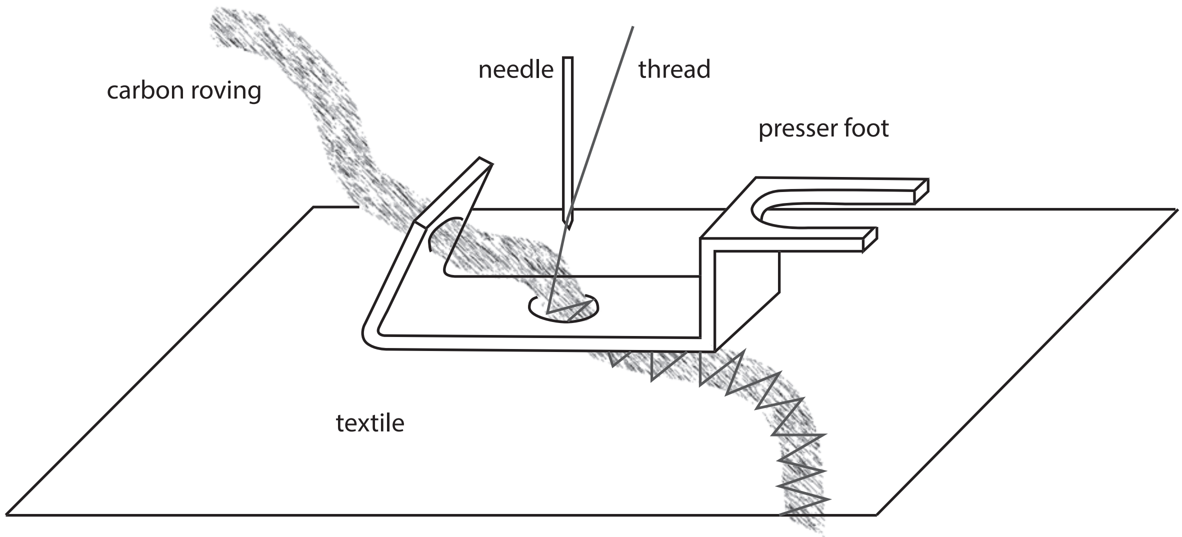


Figure 003. Principle for tailored fibre placement.

“The main advantage, compared to common textile technologies, is the ability to arrange reinforcing fibres in every direction of the reinforcing area from an angle of 0° to 360°. Accumulation of the fibres is achieved by stitching several times across the same area. In this way the preform is tailored to the stresses in the specific component.” (P. Mattheij, K. Gliesche, D. Feltin, 1998).

The results from the study show that TFP composite components perform better than fabric laminates, i.e. are more optimized with regard to its purpose. However, the method is stated to apply to components with a well-known load case. Also the load path needs to be sufficiently complex for this method to be interesting. If these criteria are met a high material efficiency can be gained.

Disadvantages of this method are that the stitching process can damage the fibres of the underlying fabric and locally change their direction. The needle yarn causes waviness in the textile and adds an additional weight, both by its own material and by creating space and yarn by which surplus resin can locate.

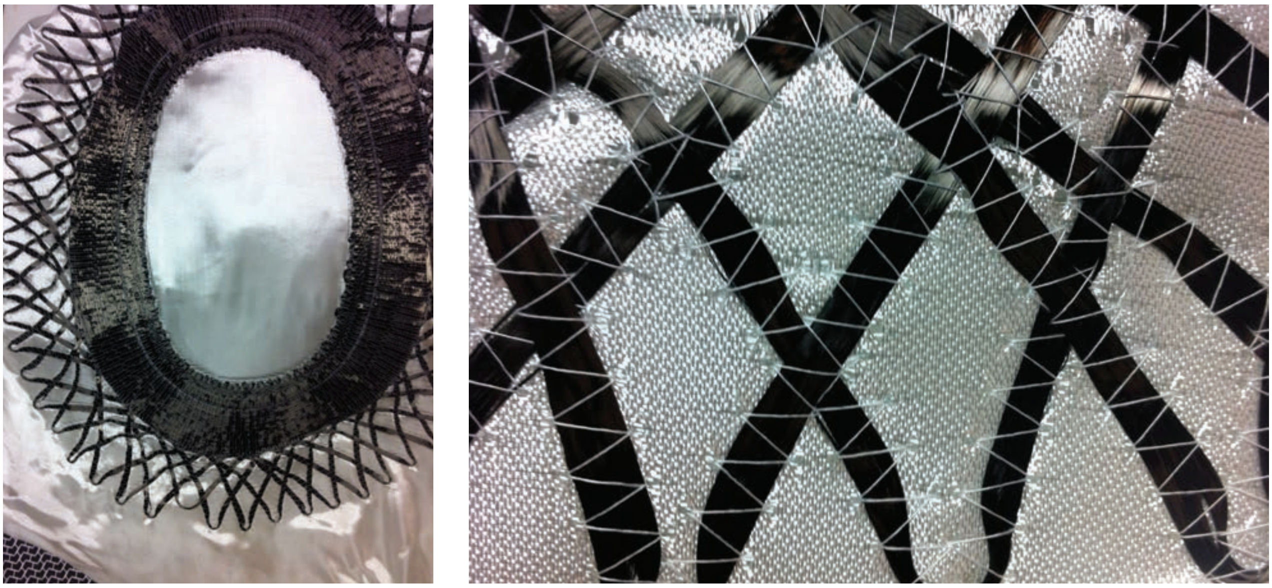


Figure 004 & 005. Example of aircraft window with embroidered reinforcement. Sicomp research project.

1.3.3 DISTRIBUTION OF FIBRES WITH FILAMENT WINDING

Filament winding is a technique used for manufacturing surfaces of revolution, such as pipes and spheres. Continuous fibre roving is fed through a resin bath onto a rotating mandrel shaping the composite. The process is very precise and high speed. With filament winding several parameters can be varied: the tension of the fibre, the amount of resin and the pattern of the winding.

An example of the use of a varied pattern is shown in figure 06. The kayak paddle developed by DJP Espace Composites shown below uses different materials and patterns to reflect the stress pattern the kayak paddle will be exposed to. Through using a clear transparent resin the winding pattern is a visible and integrated part of the design.

Figure 006. Kayak Paddle research project between Jantex and DJP Espace.

2 AIM

Within the Same Thread aims to investigate design possibilities that can influence the properties of a composite material, both aesthetically and structurally. The aesthetic expression and the static structural behavior are equally important. A special focus lies on the integration of engineering and textile design, aiming for a result where these disciplines act within the very same thread.

3 HYPOTHESIS

Textile design and materials engineering can through an iterative design and analysis process, using physical prototypes, create an innovative way of working with form and forces in a fibre composite material.

4 METHOD

The design process is driven by testing different ways of distributing and orienting the reinforcing fibres of a composite material through prototyping.

The method and communication is a central part to this thesis work. The iterative process of integrating textile and structural design is illustrated in the diagram below. The arrows crossing over between the disciplines show the most critical connections where communication was essential to move the work forward. The process started with the evaluation of a proposed textile technique, and the different textile types possible was then related to an analysis. From this we made full scale prototypes and evaluated.

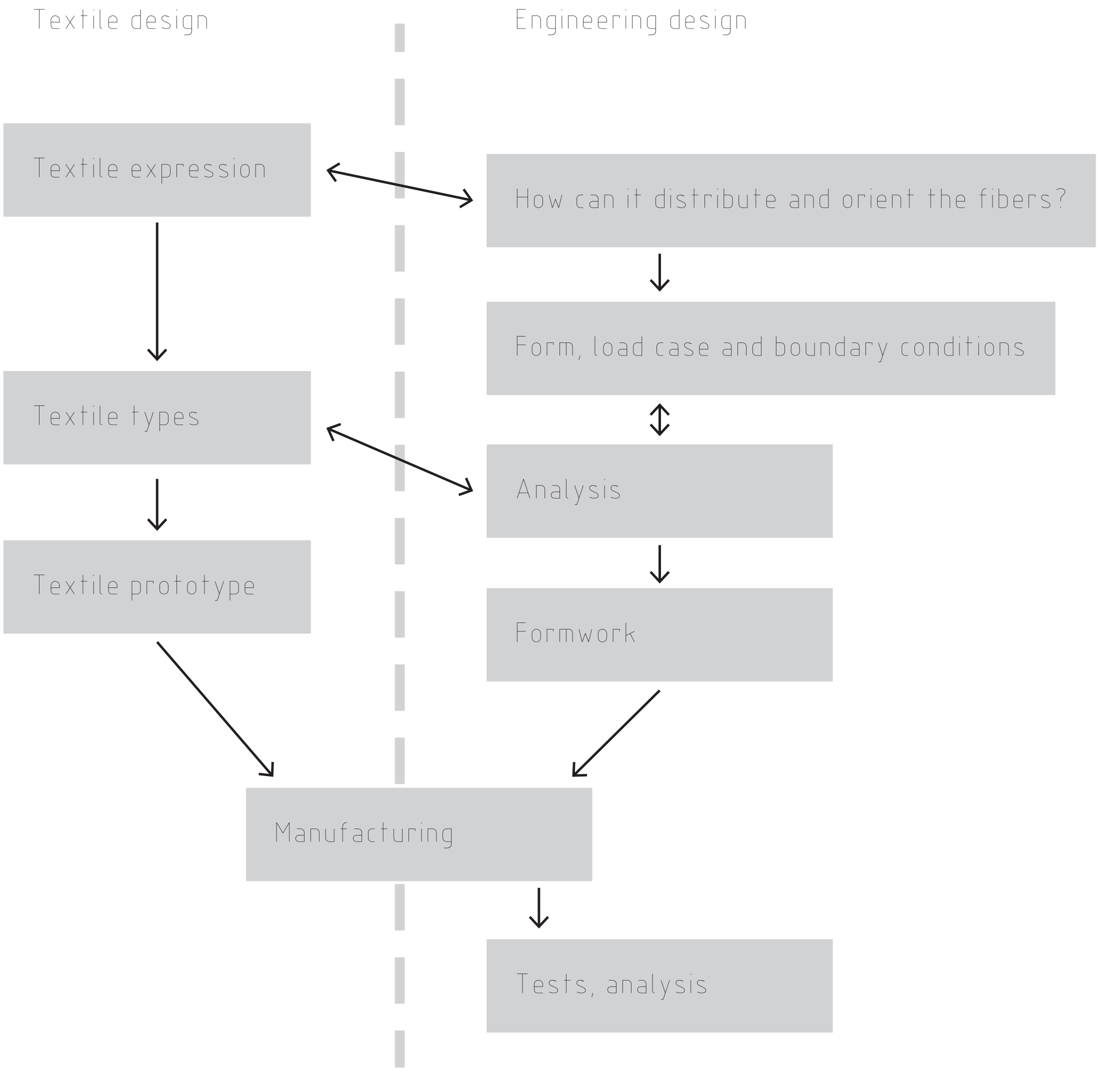


Figure 007. Schematic flow chart of the design process.

We worked with a starting point in the initial design investigations by Therese Amus Gidlöf and discussed the possibilities with her textile samples. Then we evaluated these for potential engineering properties. A form where the techniques can be applied was developed and analyzed. The stress analysis was then communicated as a basis for the textile layout. This was then fabricated and a formwork was manufactured. Finally the test samples were manufactured to evaluate the design.

5 PROJECT BACKGROUND

5.1 TEXTILE AND ENGINEERING STARTING POINTS

This thesis work is a collaboration between structural engineering and textile design. The common ground is the aim for a structural textile.

Therese Amus Gidlöf is a textile designer pursuing her bachelor's degree at Swedish School of Textiles, at University of Borås. Her initial investigations, prior to our collaboration, regarded coarse braided samples casted in silicon using molds and samples of wool braidings. Materials used at this stage was wool of coarse qualities from a collaboration with Båvens Spinnhus.

Figure 008. Braiding cast in silicon.

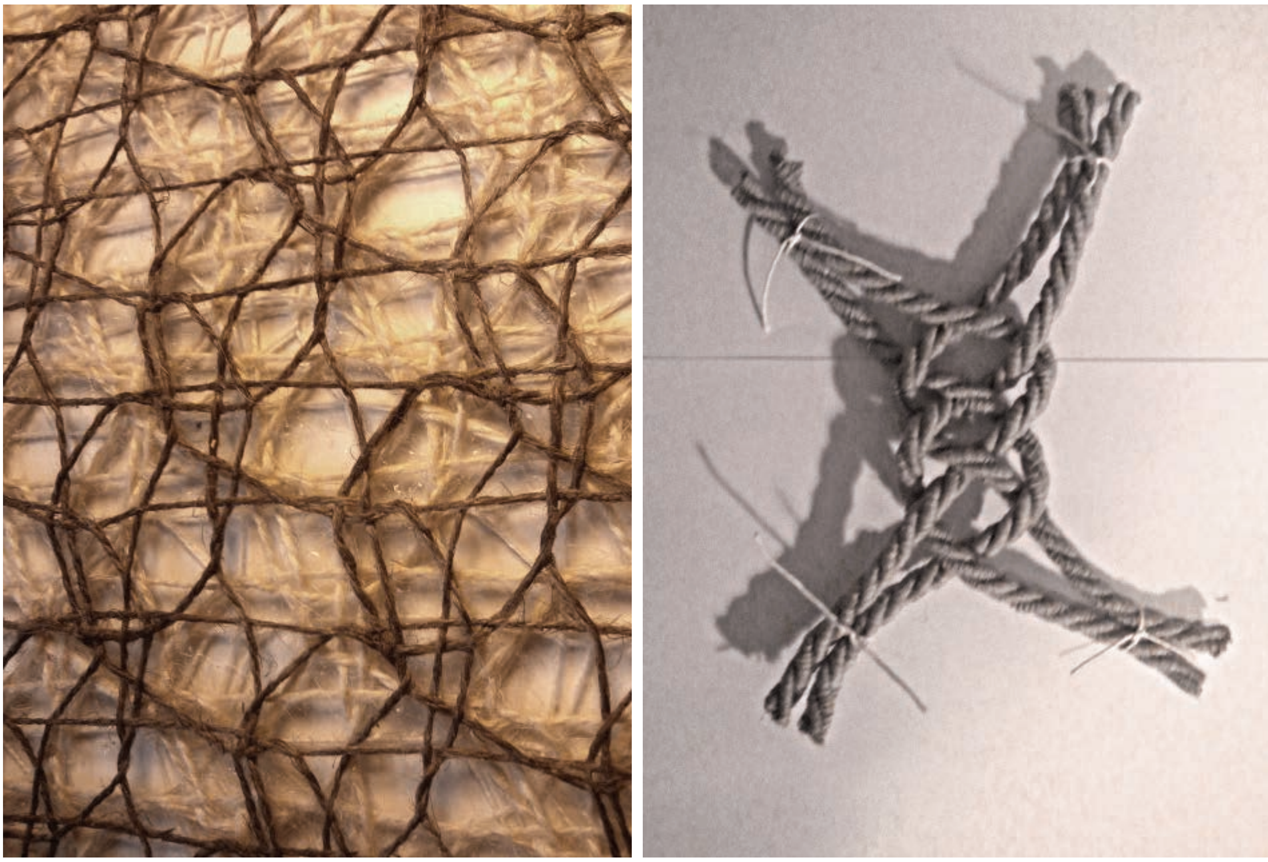


Figure 009 & 010. Early samples of braiding design investigation.

The engineering starting point was the idea to innovate composite materials through textile expression and technique. Through the knowledge and expertise on textile techniques that Therese brings, a more integrated relationship between textile and composite material can be investigated. The structural design benefits from integration with the design of the textile reinforcement. The fibres can be distributed and oriented with great amount of control, which influences the material properties of the composite.

5.2 REFERENCES

In most cases composite materials have a surface treatment that hides the underlying textiles. But in *Dining Armchair Wood* by American designers Charles and Ray Eames from 1950 (figure 011) the non-woven fiberglass structure is used as an aesthetic and structural material. It was part of the Low Cost Furniture exhibition at Modern Museum of Art in New York and employed the knowledge and machinery formerly used for war time equipment. The fiberglass textile is casted with polyester resin and the surface is polished to a marble like effect. The chair is one of the earliest uses of fiberglass as an aesthetic material (Victoria & Albert Museum catalogue).

Figure 011. DAW (Dining Armchair Wood) by Charles and Ray Eames, produced by Zenith Plastics Co. and Herman Miller, 1950.

Another important reference for composite furniture is *Knotted Chair* by Dutch artist Marcel Wanders, 1995. Wanders uses polyester and aramid fibres in a macramé knotted pattern infused with epoxy to create the shape of this chair (MOMA catalogue, 1996). The knotted structure is super textile and appears to be defying gravity with its soft appearance. The structure is also tactile in a double sense - it feels like both textile and plastic.

Figure 012. Knotted Chair by Marcel Wanders, 1995.

5.3 PROJECT IDEA

Our idea was to design a chair and prototype it in full scale. A chair has a defined load case and a size that is possible to manufacture without too large costs. The analysis of the chair will influence the textile design, and vice versa.

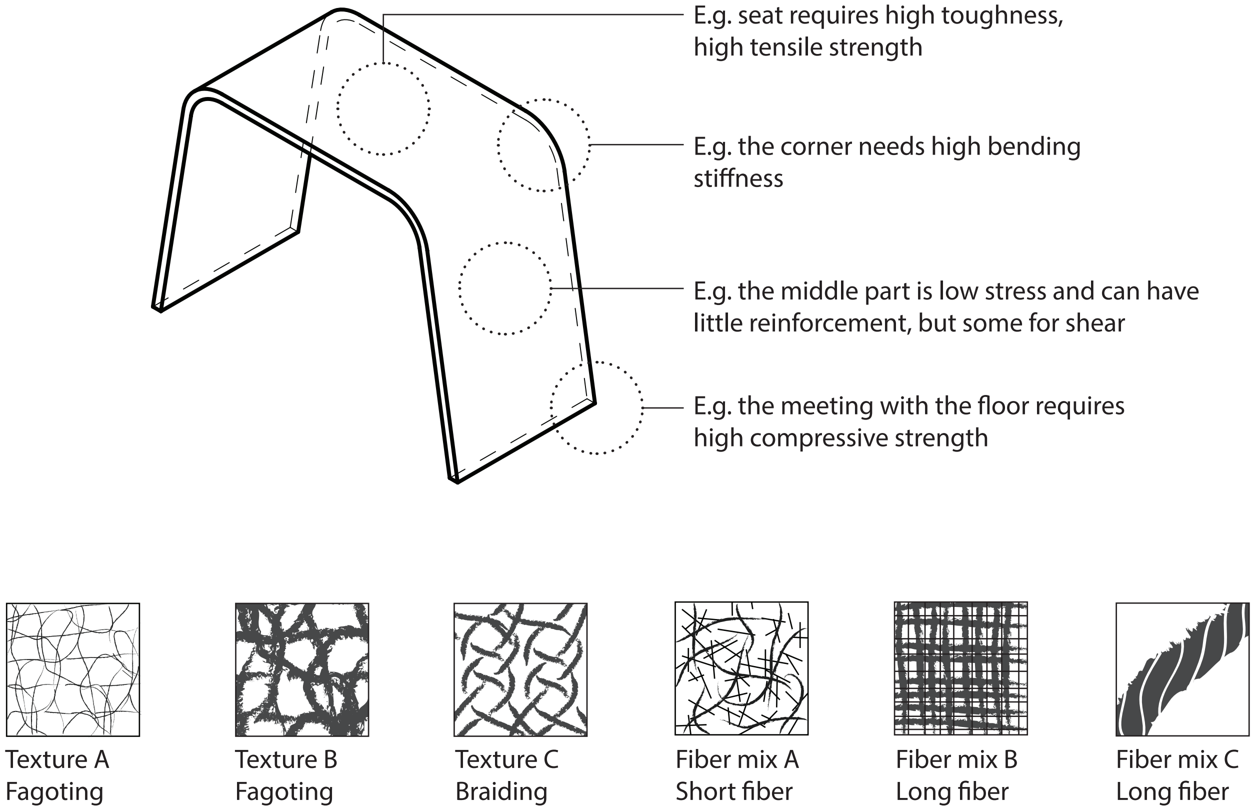


Figure 013. Project idea, initial sketch.

6 INITIAL SAMPLE MANUFACTURING

The initial samples manufactured was made using simple products. We created plastic molds in A-verkstaden and used material samples in wool from Båvens spinnhus together with fiberglass. The investigation regarded the appearance of wool, possibilities for relief surfaces and coarse braiding techniques.

Figure 014. Nonwoven wool cast into plastic mold. Epoxy resin.

Figure 015. Left: Plastic mold, fibreglass epoxy. Right: Plastic mold, grey wool, epoxy (small amount).

Figure 016. Coarse brading in wool, fibreglass, epoxy.

Figure 017. Coarse brading in wool used for shaping a plastic mold.

To shape our samples we created a mold from vacuum forming a plastic sheet over a coarse braid.

Though good to get a practical start it was evident that production possibilities and knowledge will be important for the project result. The samples are a bit slimy and unpleasant in their partly plastic and partly woolly finish. The choice to work with relief surfaces on the other hand seemed promising as the textile becomes not only an image but also a tactile shape.

7 BRAIDING TECHNIQUES

The early tests and ideas that Therese made was coarsely braided wool and flax cast in silicon. From the engineering side the idea of composite materials came, and we started working with braiding and how braids could be employed in a structural material.

The design idea was a very coarse and modern style of braiding in wool. Since wool is not a particularly strong material we tried to mix it with fibres that also had higher strength. Both the expression and the structural function of the braids were developed through collaboration with Remfabriken in Gothenburg. Remfabriken is an industrial history museum where a part of the machine park is still functioning. Production stopped here in 1977 and many machines are from the turn of the century. This offered possibilities for making very coarse braids not possible at Textilhögskolan's machine park in Borås.

Figure 018. Left: Mechanical string braiding machine. Right: The machine braids around a core yarn.

The braids were constructed with a core yarn and several yarns braided around it by the machine. As mentioned above we used wool from our supplier Båvens Spinnhus and this was combined with the much stronger materials flax and kevlar.

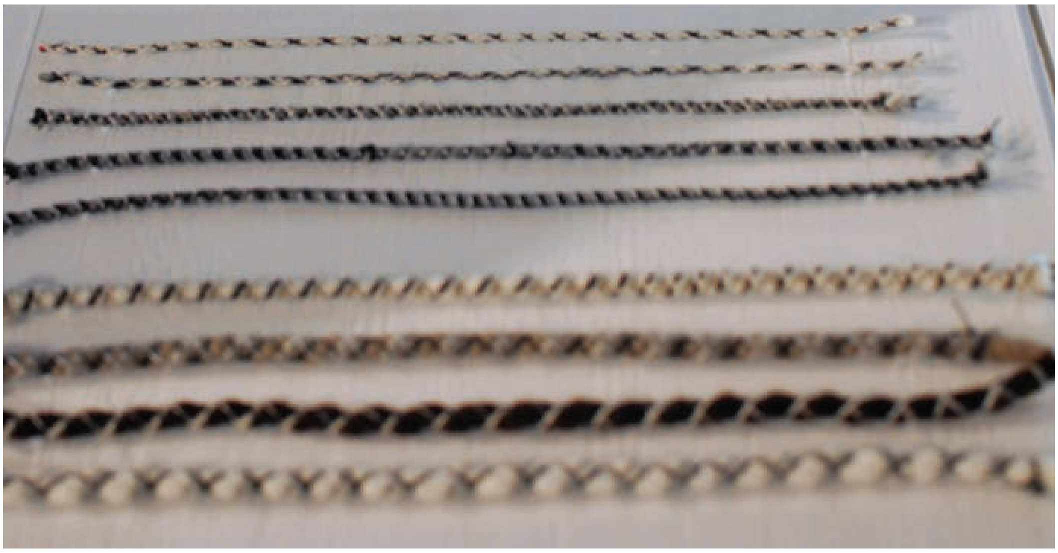


Figure 019. Braids. Coarse braids have wool cores and thin braids kevlar cores.

The cores were wool or Kevlar and the yarns braided around them were wool and flax in natural colours. Kevlar is the trade name for a paraaramid fibre developed by DuPont in the late nineteen sixties. It is five times stronger than steel in relation to weight. Kevlar is not as brittle as for example carbon fibre, which made Kevlar suitable for our application.

Figure 020. A:Kevlar core with wool and flax braids. B: Coarse wool core with wool and flax braids. C: thin wool core with wool and flax braids. D: Flax weaves for composite application, textile single direction 90° weave. E: Flax weaves for composite application, plain weave.

The braiding constructed from these manufactured braids at Remfabriken. Braiding can be made into patterns that distribute the fibres to where reinforcement of the composite is needed. But the method is labour intensive and time consuming. It is a complex technique to carry out and therefor adaptation between pattern and analysis may prove to be difficult.

Our composite samples with braids and braiding are presented in chapter 12 & 13. Chapter 11 presents our first test composite samples with braided textiles.

8 JACQUARD TECHNIQUES, PART 1

Although braiding had strong aesthetic qualities, braiding as technique and the braids had technical problems difficult to solve. The scale was very large and the knots created unwanted thickness to the final result. We therefor started looking into weaving, a more conventional way of making textiles for composites.

The jacquard weaving technique is used for weaving complex patterns and the jacquard loom was even the first application of the punch card, or early programming. The pattern from the previous braiding samples is used as an inspiration for Therese Amus Gidlöf in exploring possible expressions in weaving.

Figure 021. Digital jacquard loom at Textilhögskolan.

The challenge with the jacquard technique is that even though the pattern has variation in material or colour, the weave has equally distributed threads all over its surface.

To overcome this problem we try weaves with picks of plain and floating weft, and cutting technique. You can cut either the warp or weft or both, as can be seen in the schematic image below.

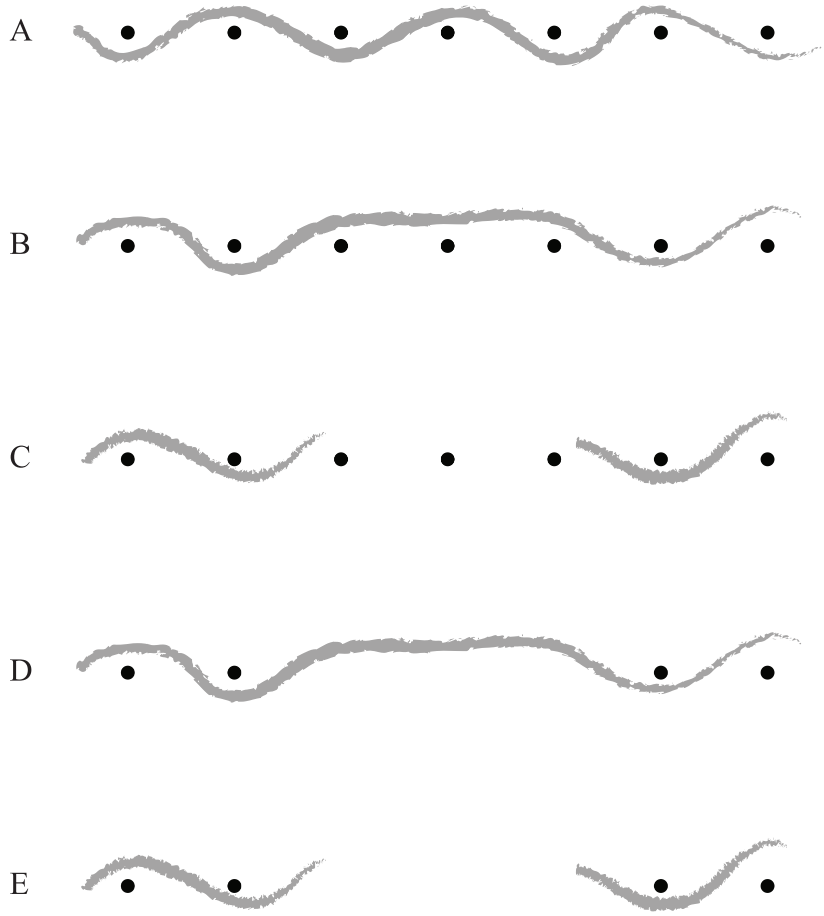


Figure 022. Schematic section through different weaves. A: Regular weave, B: Float technique, standard, C: Float technique with cut weft, D: Float technique with cut warp, E Float technique with both warp and weft cut.

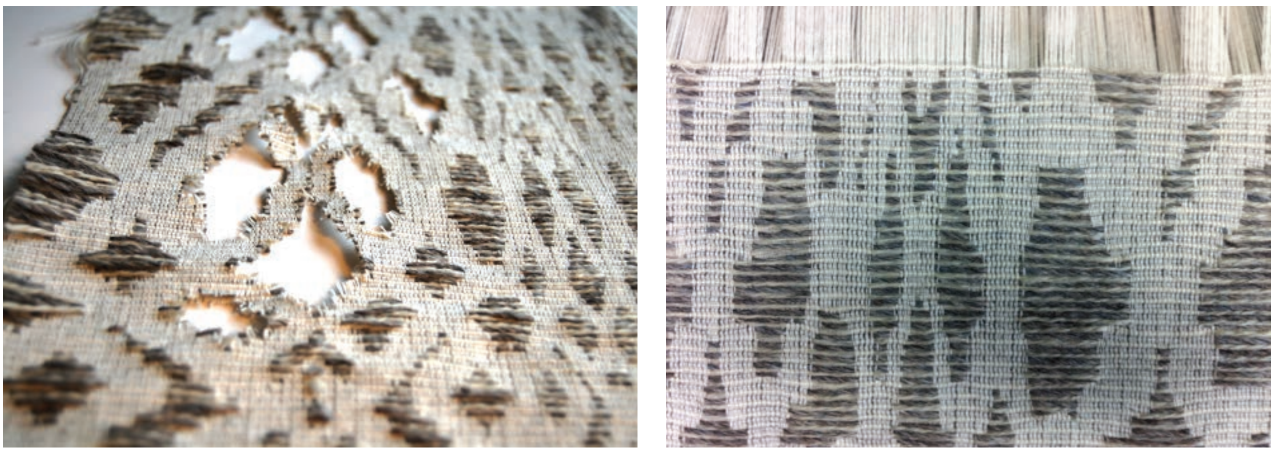


Figure 023. The grey wool yarn continues over the warp without going under it, as described in the schematic images above. Left: In this sample the parts done in float technique are cut. Right: The grey areas are in float technique.

Therese Amus Gidlöf developed several graphic and expressive samples with this pattern idea, as shown in the images below. The warp is white cotton and the weft is different coloured wool from Båvens Spinnhus.

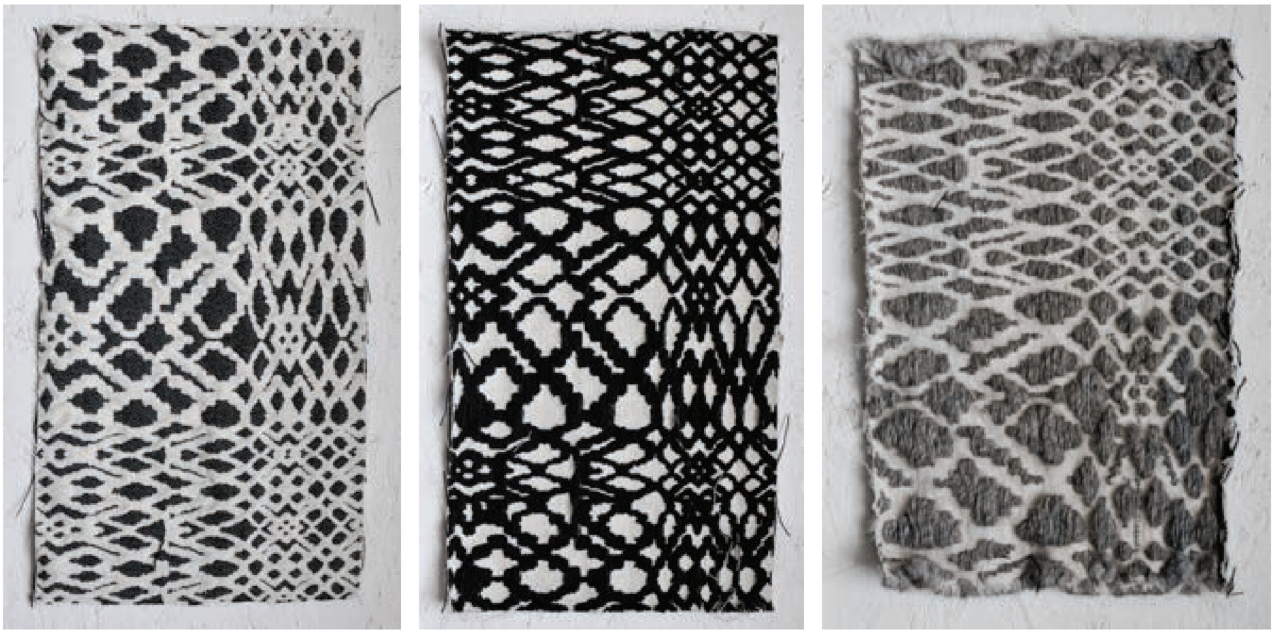


Figure 024. Textile samples of braid inspired patterns in jacquard weave with float technique.

A draw back from the float technique and cutting technique is that the threads, and the reinforcement of the composite, is cut at short lengths, as illustrated below. The distribution of material can be varied and adjusted after an analysis, but the anchoring length is too short for structural purposes. The ideal would be a continuous thread.

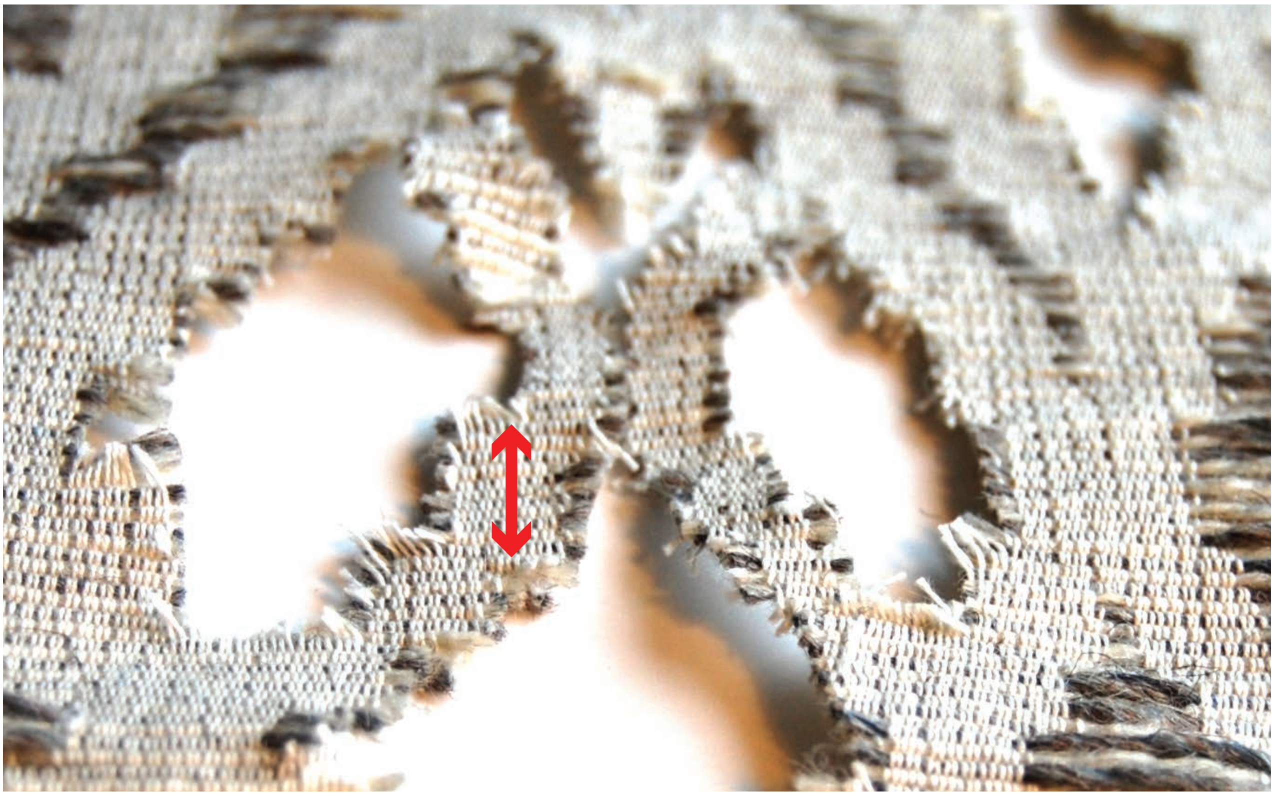


Figure 025. Illustration of thread lengths in jacquard samples.

We had issues with decolouration of the white wool segments, as can be seen in the image below. The epoxy resin has a tendency to turn yellow as it sets, and this increases during its lifetime if exposed to UV-light. We therefor tried dying a sample in cyan-turquoise nuance. This sample turned out beautiful, but the coloration was much too strong to only compensate for the white parts but rather gave a new expression, see the images below.

Figure 026. Composite samples with o the left white cotton weft and grey wool and to the right the same composition dyed prior to injection.

9 FORM 1

9.1 SHAPE INVESTIGATION

The first form we tried out for the chair was based on flat surfaces. We did not know if we could manufacture any other shape, so we investigated different configurations with planes.

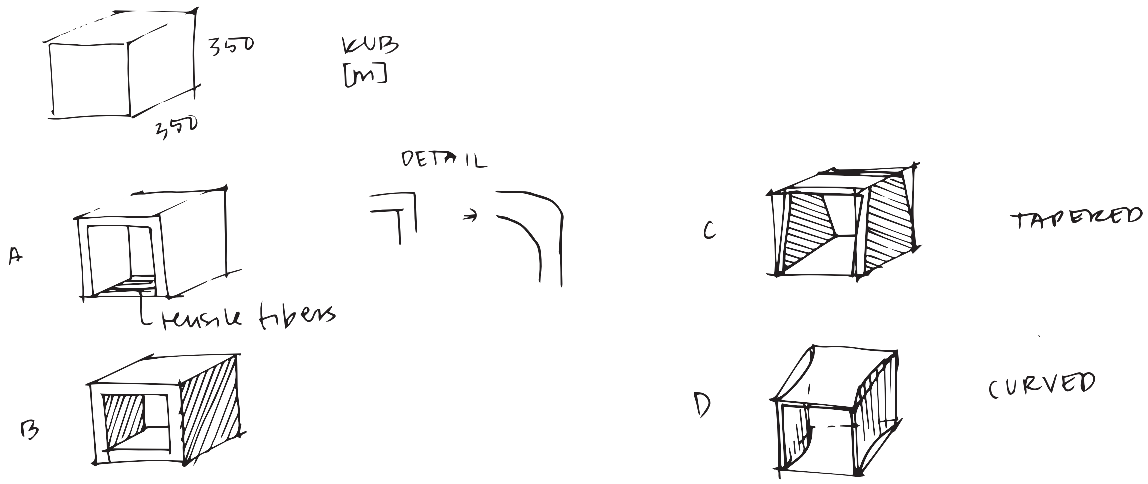


Figure 027. Form studies.

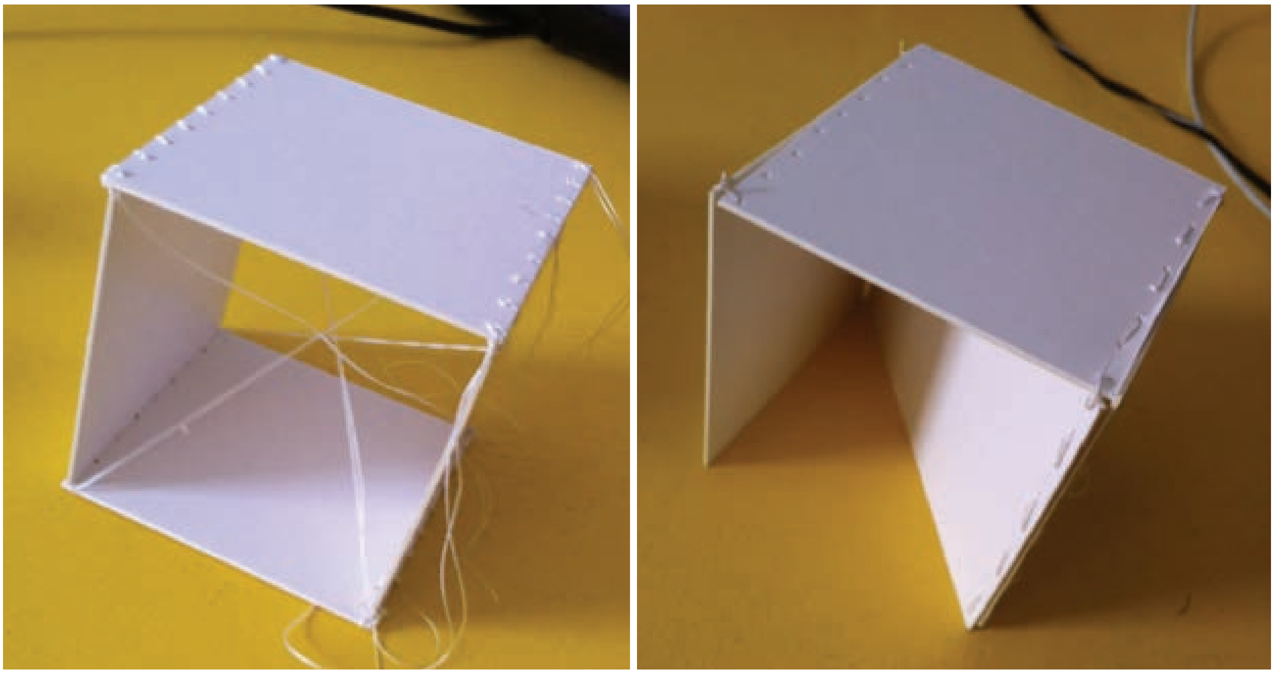


Figure 028. Chairs of plane surface shapes.

The studies where examined with regard to

1) manufacturing possibilities
2) expression
3) showcasing the textile
4) interesting force pattern

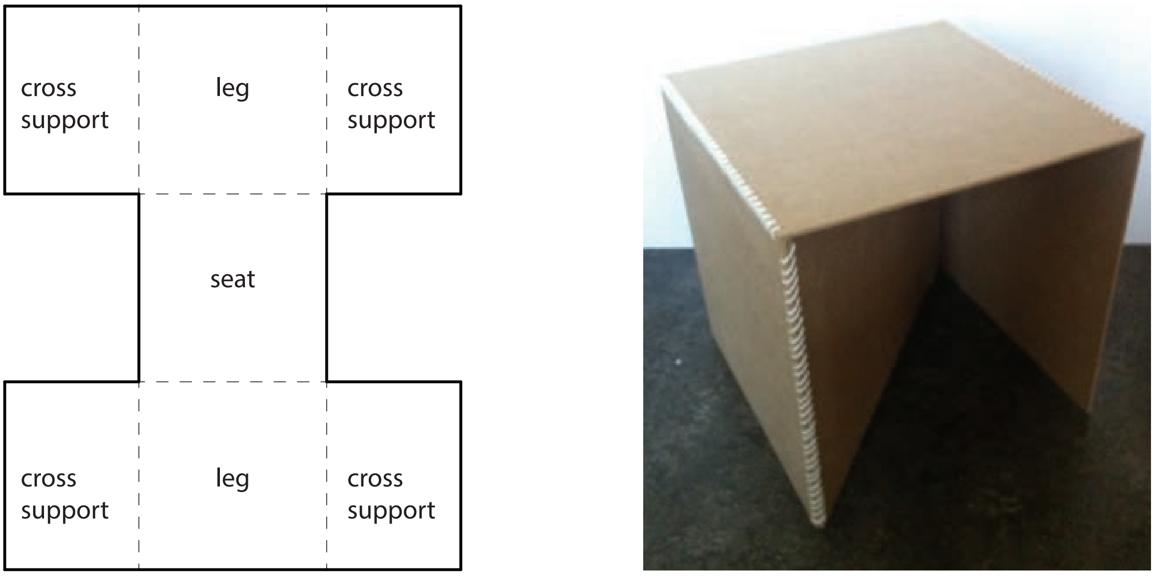


Figure 029. Left: Flat construction drawing. Right: 1:1 prototype in mdf-board.

From the sketches, scale models and 1:1 model (figure 029) we decided to look further into the chair idea (figure 030). We examined and discussed force paths and stability, as well as positioning of connection details.

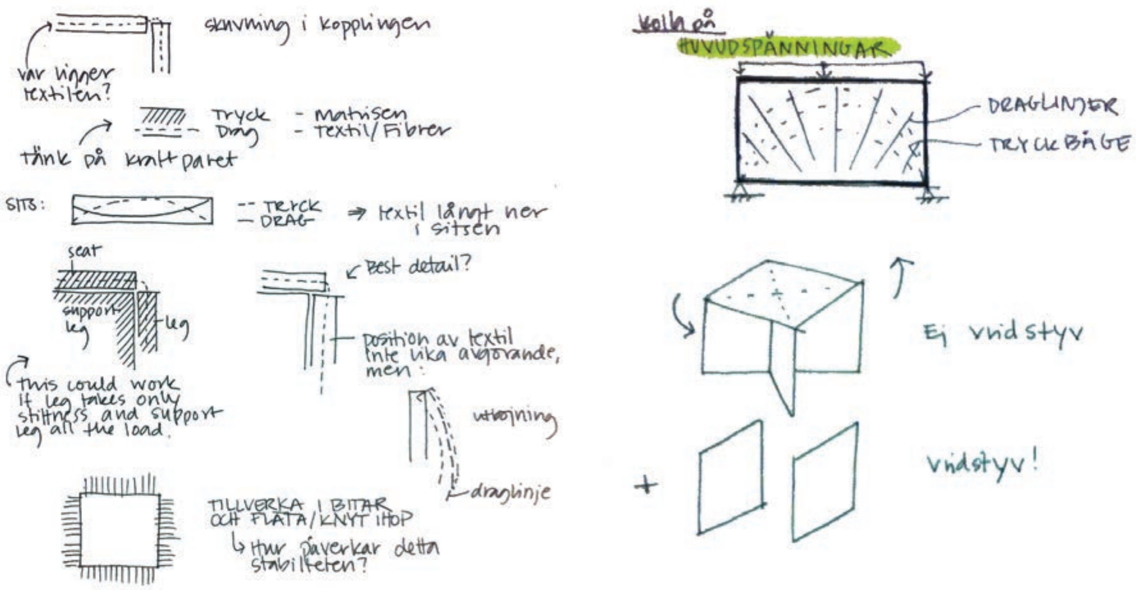


Figure 030. Sketches from the process. Details, force paths and stability issues.

9.2 FE - ANALYSIS AND RESPONSIVE PATTERN

To draft the rules for the textile pattern we carried out FE-analyses, isolating each plane of the chair and simulating them separately. The pattern would be responsive to maximum and minimum stresses, or compression and tension. We also considered von Mises stresses to find stress concentrations that our design should address. For the FE-analysis the simplified FE-software Force Pad was used. A generic, isotropic and linear elastic material is sketched and boundary conditions and forces are applied. A distributed load is approximated by a series of point loads, representing someone sitting in the chair. The analysis is 2D.

We made several tests with different boundary conditions and decided that even though the sides or

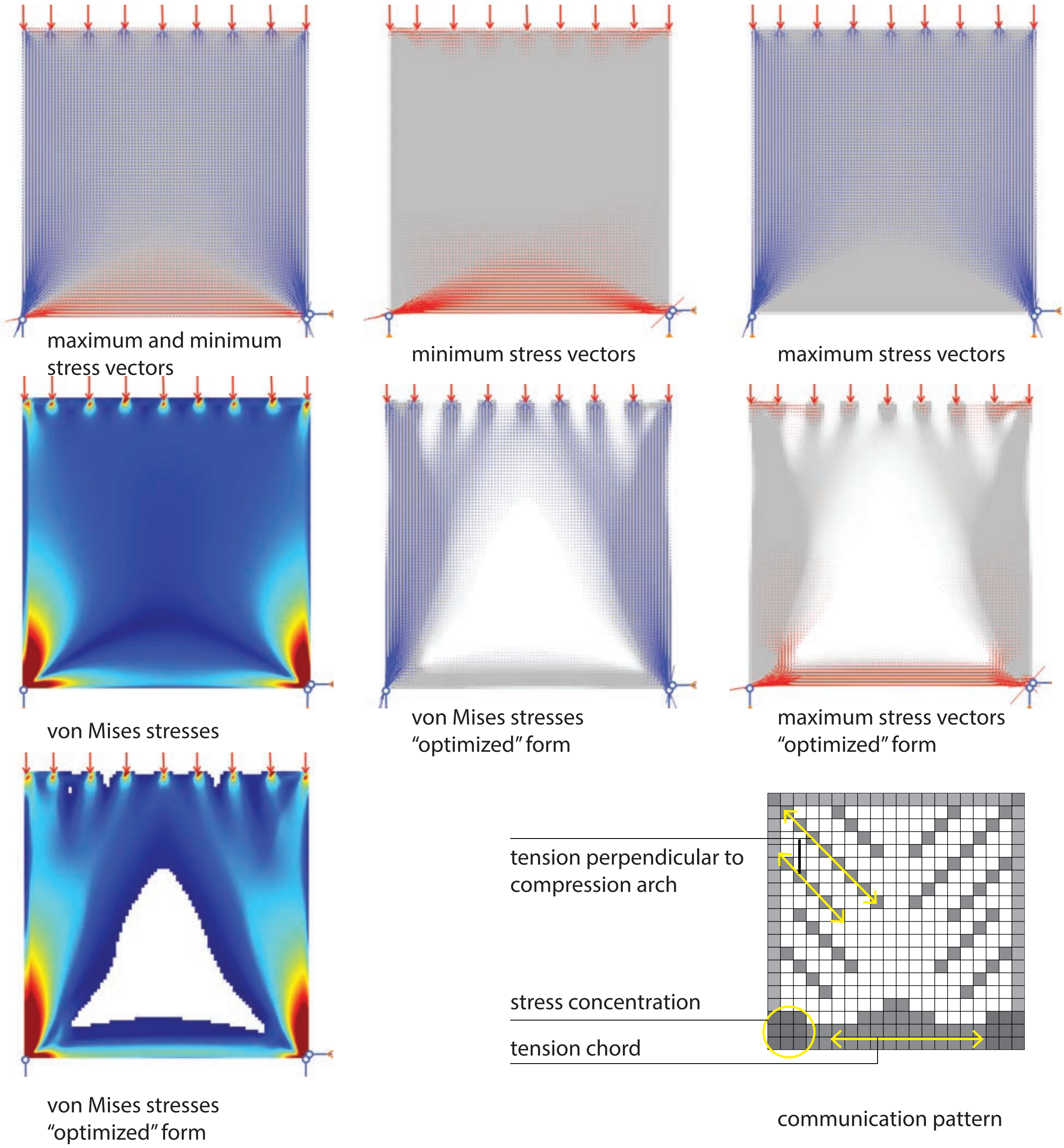


Figure 031. FE-analysis (ForcePad) and resulting communication image at the bottom right.

legs of the chair are supported along their length, this does not create a very challenging pattern of stresses to adopt the design to. Therefor we chose to design for two supports. By placing the fibres of our design according to this analysis we shape the stress pattern into a simply supported structure, even though it is supported all along the edge. The force will choose the stiffest way through the material, and therefor the interaction between analysis and textile design can go both ways.

The communication pattern takes into account the concentration and direction of the minimum stresses in the material, since the textile reinforcement primarily improves performance for tension stresses. The pattern is also adapted to stress concentrations at supports. A frame is added for rigidity, this is an addition not resulting from analysis but from a sense of the engineer. The different shades of gray represents concentration. The direction of the forces was communicated through discussion.

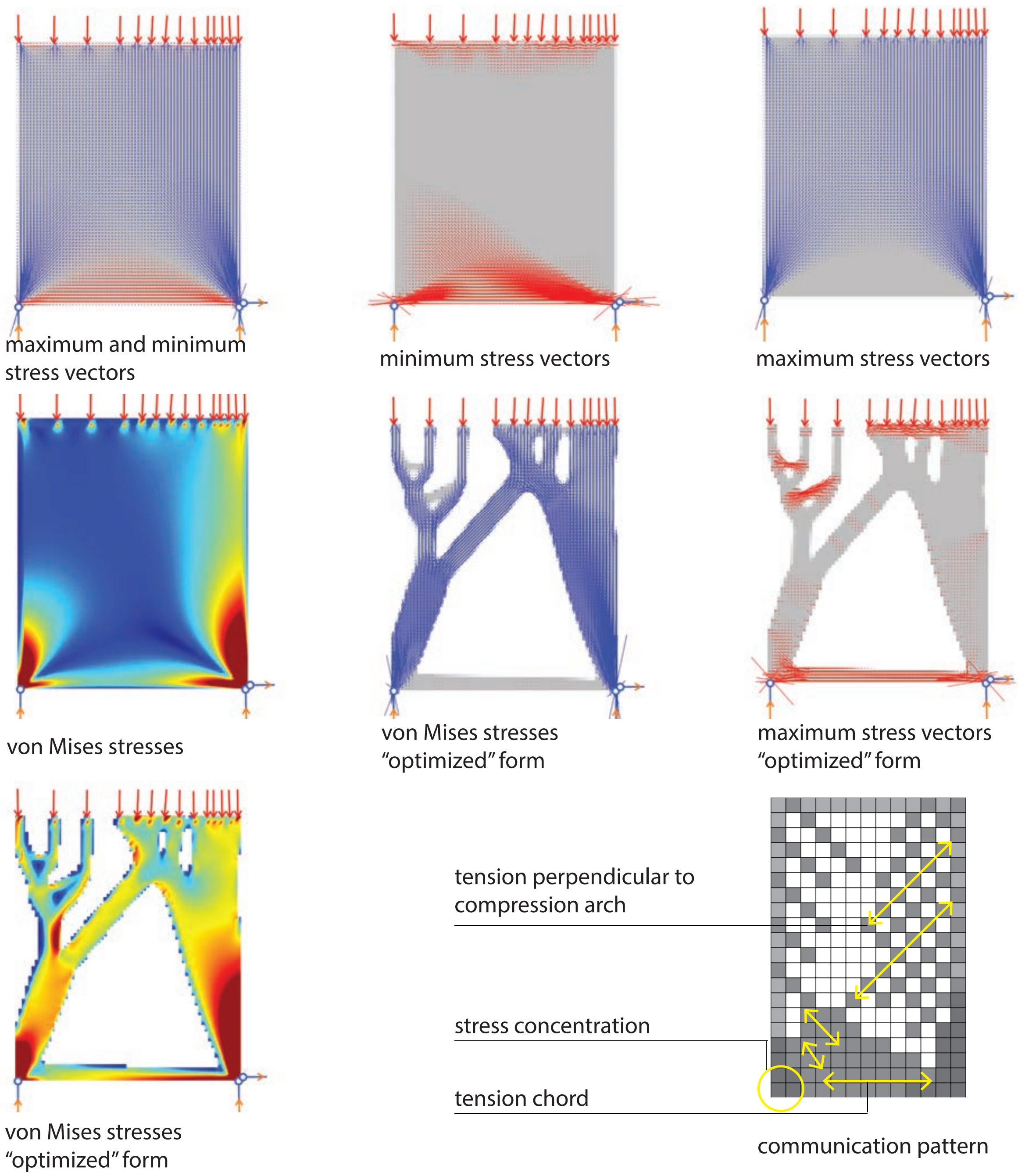


Figure 032. FE-analysis (ForcePad) and resulting communication image at the bottom right.

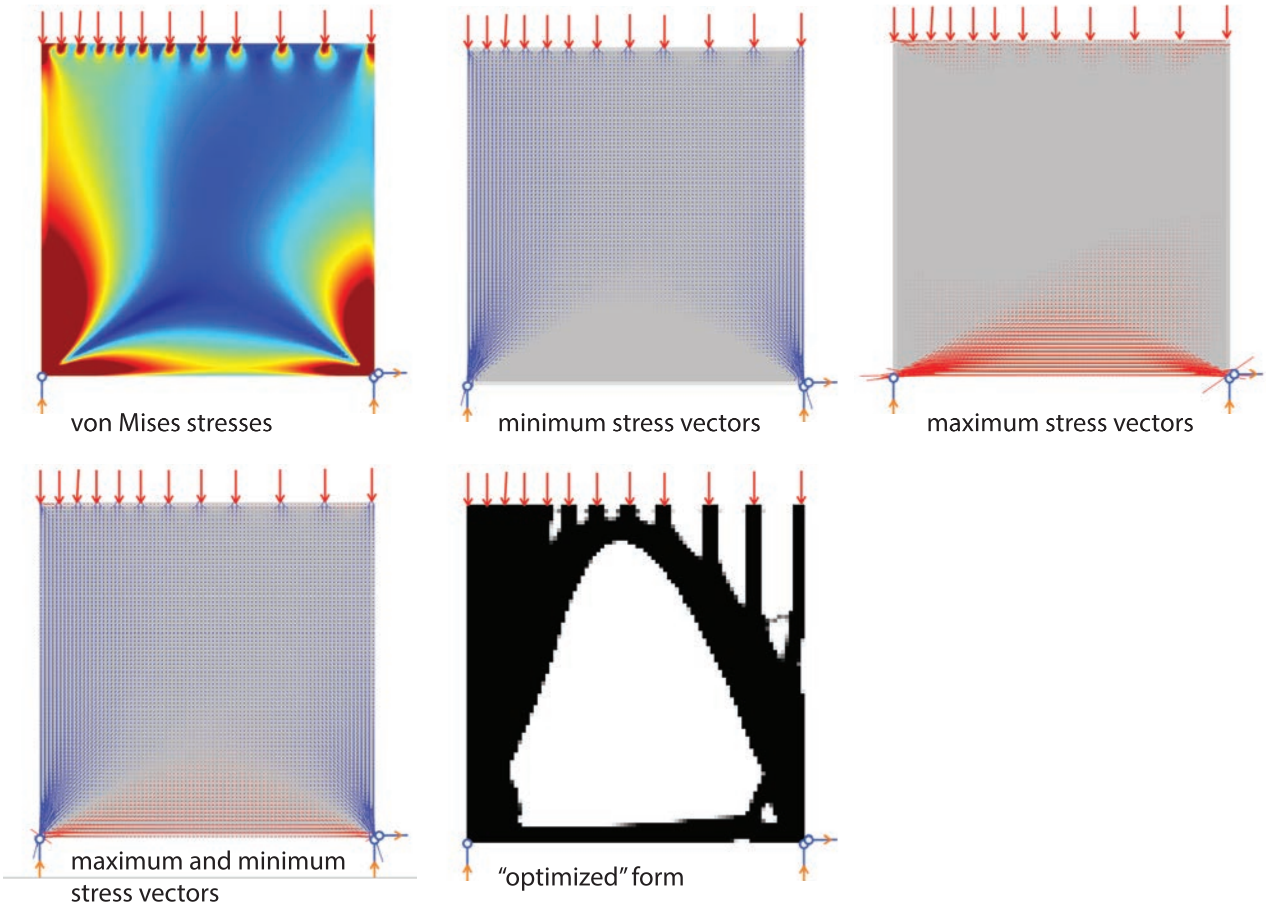


Figure 033. FE-analysis (ForcePad)

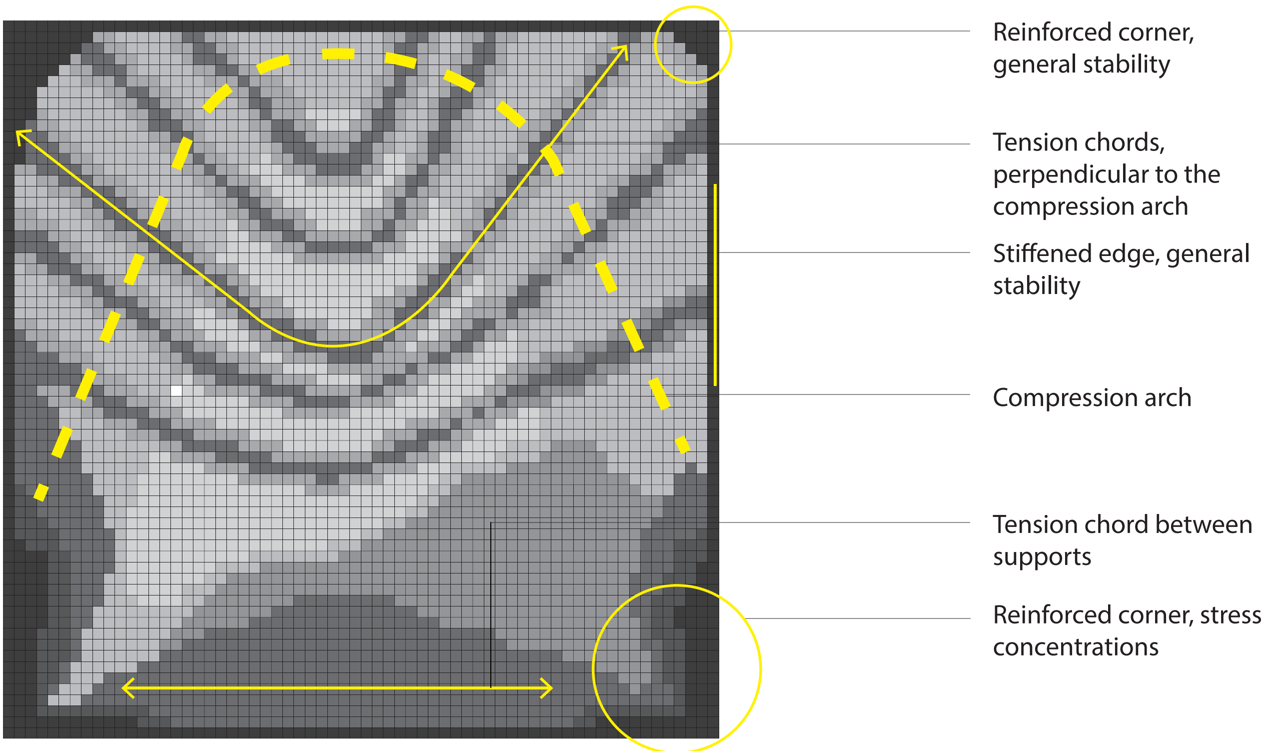


Figure 034. Detailed communication pattern.

The initial patterns were too coarse to work with for the textile pattern. We therefor developed a high resolution communication (figure 034) for creation of the responsive pattern and this was developed into a textile pattern (figure 035).

This pattern was however never woven since we changed form before production of this pattern took place.

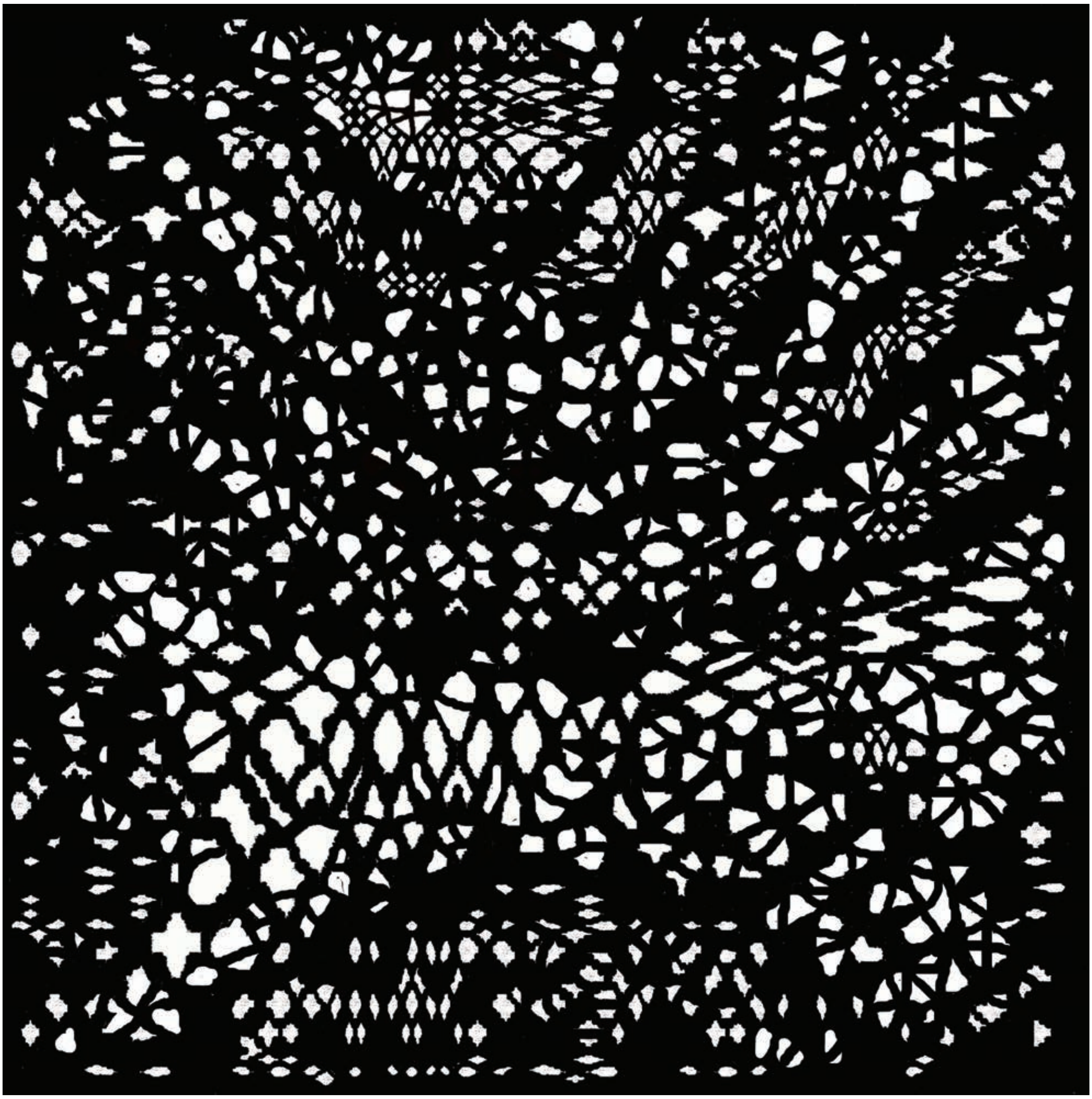


Figure 035. Textile pattern responding to analysis. For jacquard weave.

10 SAMPLE PROTOTYPES

Our first sample (presented in chapter 8) made with hardware store products was not of the quality and precision we wanted, and to handle these chemicals outside a laboratory is dangerous. Through our supervisors at Chalmers we got in contact and started collaborating with Swerea Sicomp in Sisjön, Gothenburg.

For our first visit we were introduced to the laboratory and made three test samples under Maciej Wysocki's supervision. Before the visit we had discussed suitable manufacturing techniques. Epoxy infusion would allow us to have a relief surface and we decided on this procedure.

Our set-up is described in figure 10.1. The manufacturing technique is called vacuum bagging. By placing the textiles on a tool, covering it with PE-foil (polyethylene-foil) and closing the edges with tacky tape you build a vapour tight bag around your laminate. At one end the epoxy is let in through tubing and at the diagonal end a vacuum pump builds up a pressure difference in the bag that sucks the epoxy across the laminate layers. Since the vacuum drags the bag down the laminate is compacted to achive a high fibre to matrix ratio.

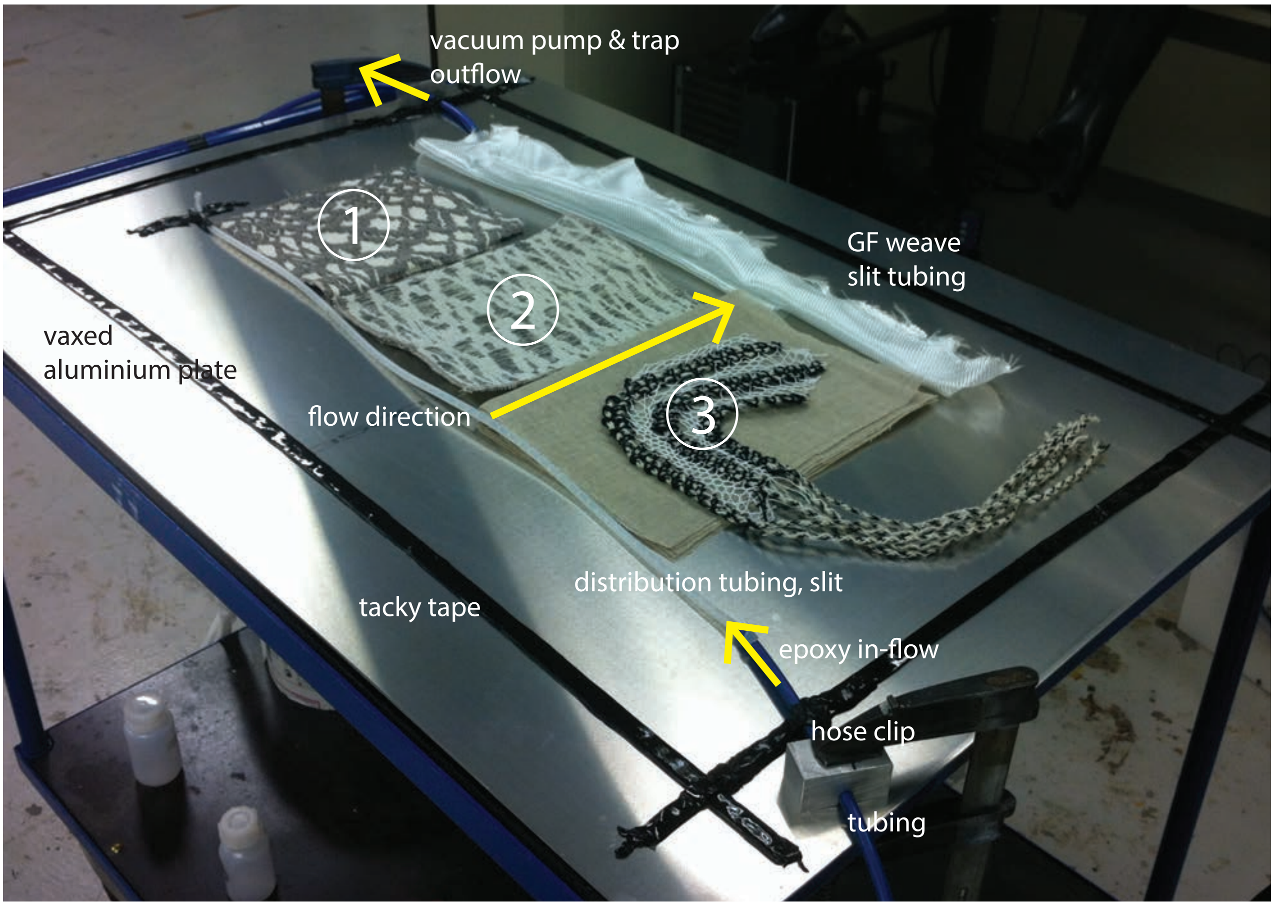


Figure 036 Set-up for the first sample infusion at Sicomp. The image does not show the PE-foil bag that is placed to cover everything when the set-up is complete.

We used a chemically waxed aluminium plate as tool. The plate is waxed to improve release of the hardened composite. The samples are placed in the middle of the plate. We used regular flax weave from a shop to get some thickness and a better idea how our full-scale prototypes may become.

The tubes inside the bagging are slit as to distribute epoxy along its length. The resistance is much larger in the laminate layers than in the tubing, which means that the diameter of the tubing is of little importance to infusion speed.

The slit tube connected to the vacuum pump is covered with GF-weave. The hollow space in the weave creates channels connecting the vacuum to the epoxy and enables the flow. The GF-weave distributes the vacuum. After hardening this weave is easily removed and thrown.

Figure 037. Upper left: Attaching the tacky tape around the samples. Upper right: Attaching the slit tubing to the regular tubing and hose clip. Lower left: PE-foil in place. Lower right: The connection between the tube and slit tube is covered to avoid puncturing the bagging.

The epoxy used for this experiment was a two-component, low viscosity product developed for vacuum infusion. It is mixed with a hardener before infusion. Mixing should be done in a fume cupboard and if possible placed in a vacuum chamber afterwards to draw out any air bubbles caused by pouring or mixing.

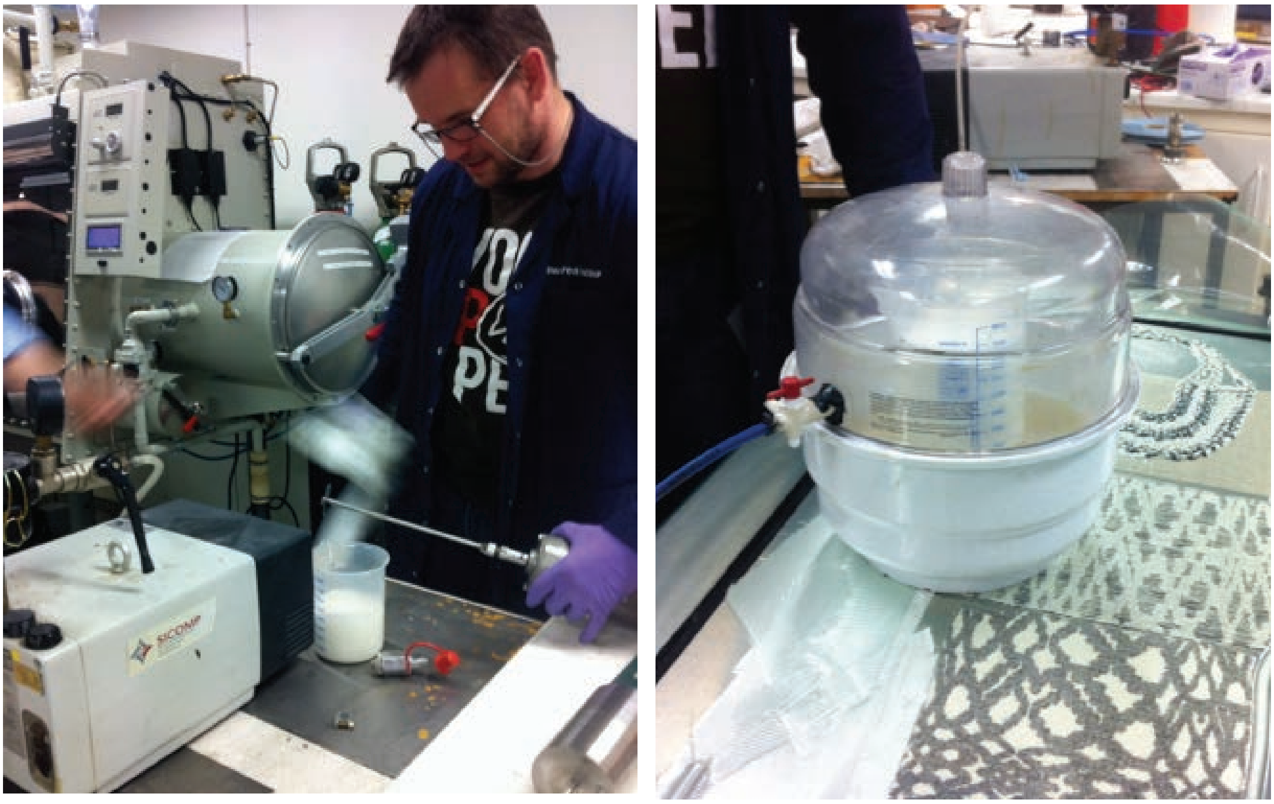


Figure 038. Left: Mixing the epoxy with hardener. Right: Eliminating air bubbles.

When the set up was done and epoxy mixed we had 1,5 hours of pot life until the epoxy hardens.

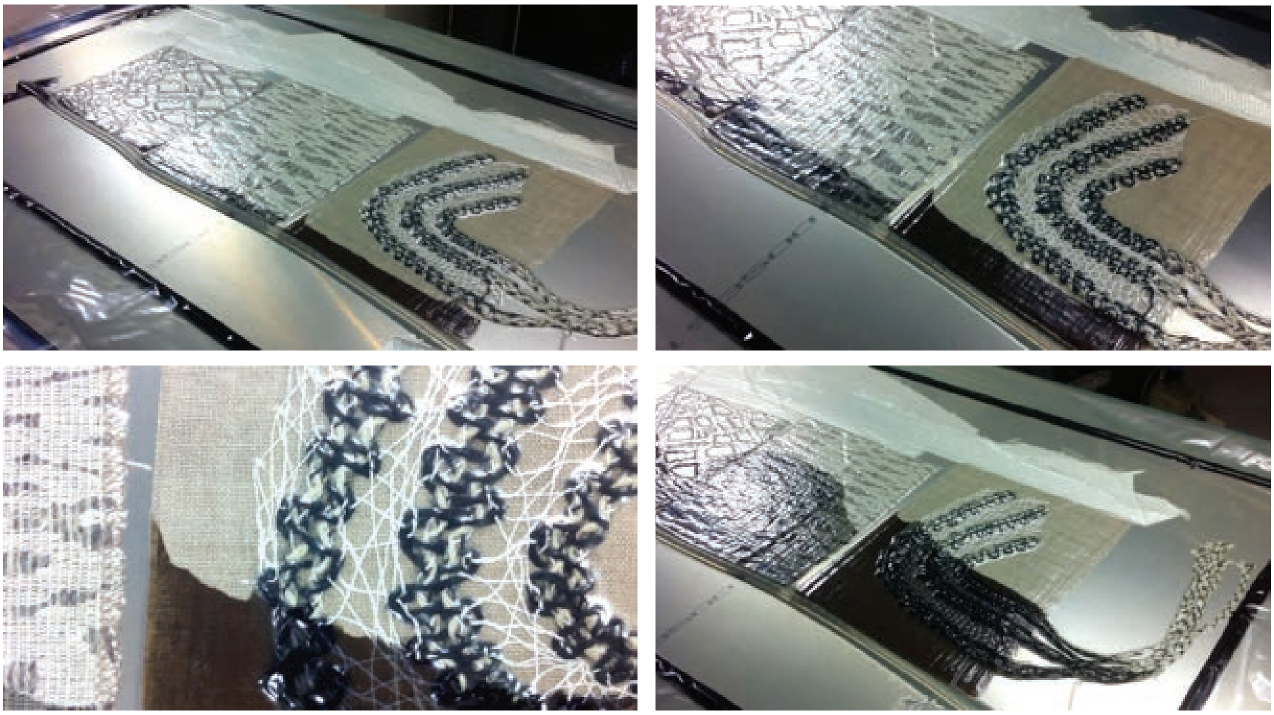


Figure 039. Top left: Epoxy infusion has just started. Top right: The vacuum holds the PE-foil so tightly to the aluminium plate that no epoxy wanders there. Bottom left: Along the rims the epoxy travels faster due to small offsets in the textile layers that create smaller resistance here. Bottom right: The injection half way.

There are two driving forces for the epoxy: pressure drop induced by the vacuum pump and surface tension. The surface tension is why the epoxy wets the "tails" of sample three even though these tails are not placed between the inlet and the outlet.

After the infusion is complete the laminate is left to harden over night before curing in a ventilated oven.

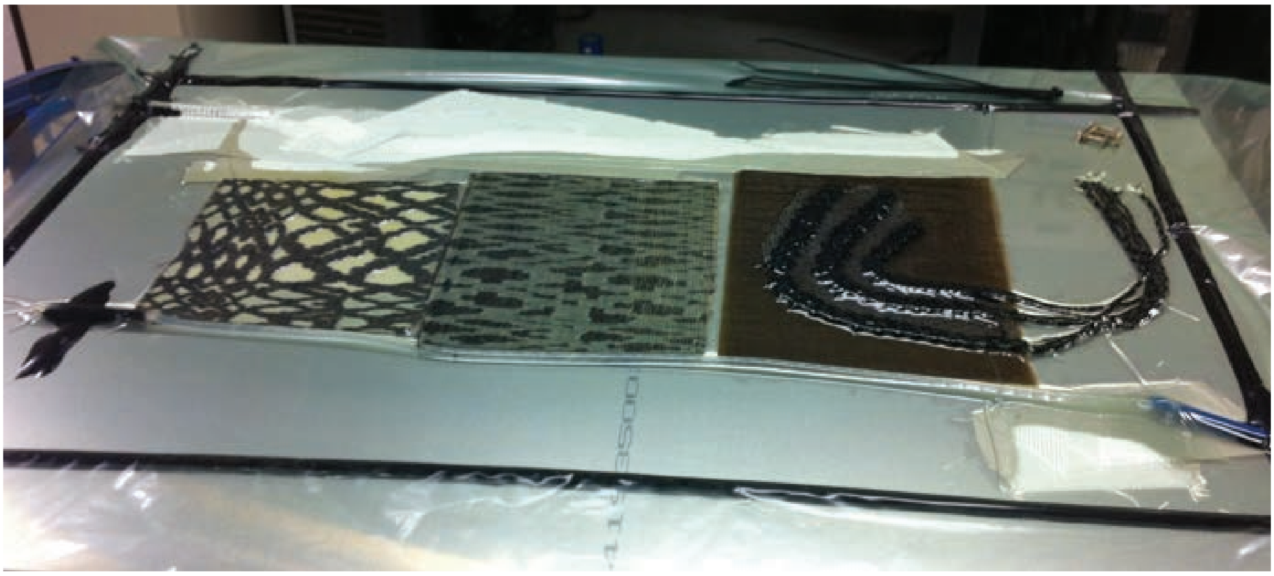


Figure 041. The infusion is completed. Part of the GF-weave has also wetted.

The samples were slightly deformed in the after curing process in the oven due to poor placing on supports in the oven. We learned that the textile changes in colour, similar to wetting in water, and decolours slightly towards a yellow tone. Sample three appeared best with light coming through the piece.

Figure 042. Finished sample as exhibited at EXIT14 at Textilhögskolan, Borås.

Figure 043. Finished sample as exhibited at EXIT14 at Textilhögskolan, Borås.

11 FORM TWO

11.1 REFLECTION ON FORM 1

The first form was a search for a plane surface combination, but as the understanding of the manufacturing possibilities develop a new form with a single curved surface are investigated. The reasons for abandoning the old form are that the connection details would be complex to solve and the many surfaces and connections would focus the attention here rather than the pattern of the textile.

11.2 FORM AND FORCE PATTERN

Trying to reach a form with an interesting force pattern led to an investigations of an ondulating shape. With new knowledge about the recent addition the foam cutter to the CTH architecture workshop making of the formwork and form prototype was possible. The cutter primarily works with single curvature cuts.

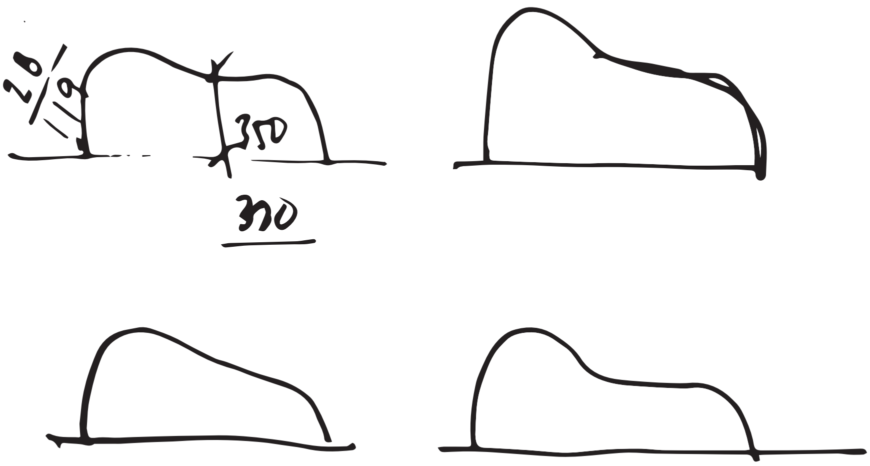


Figure 044. Sketches of the new form.

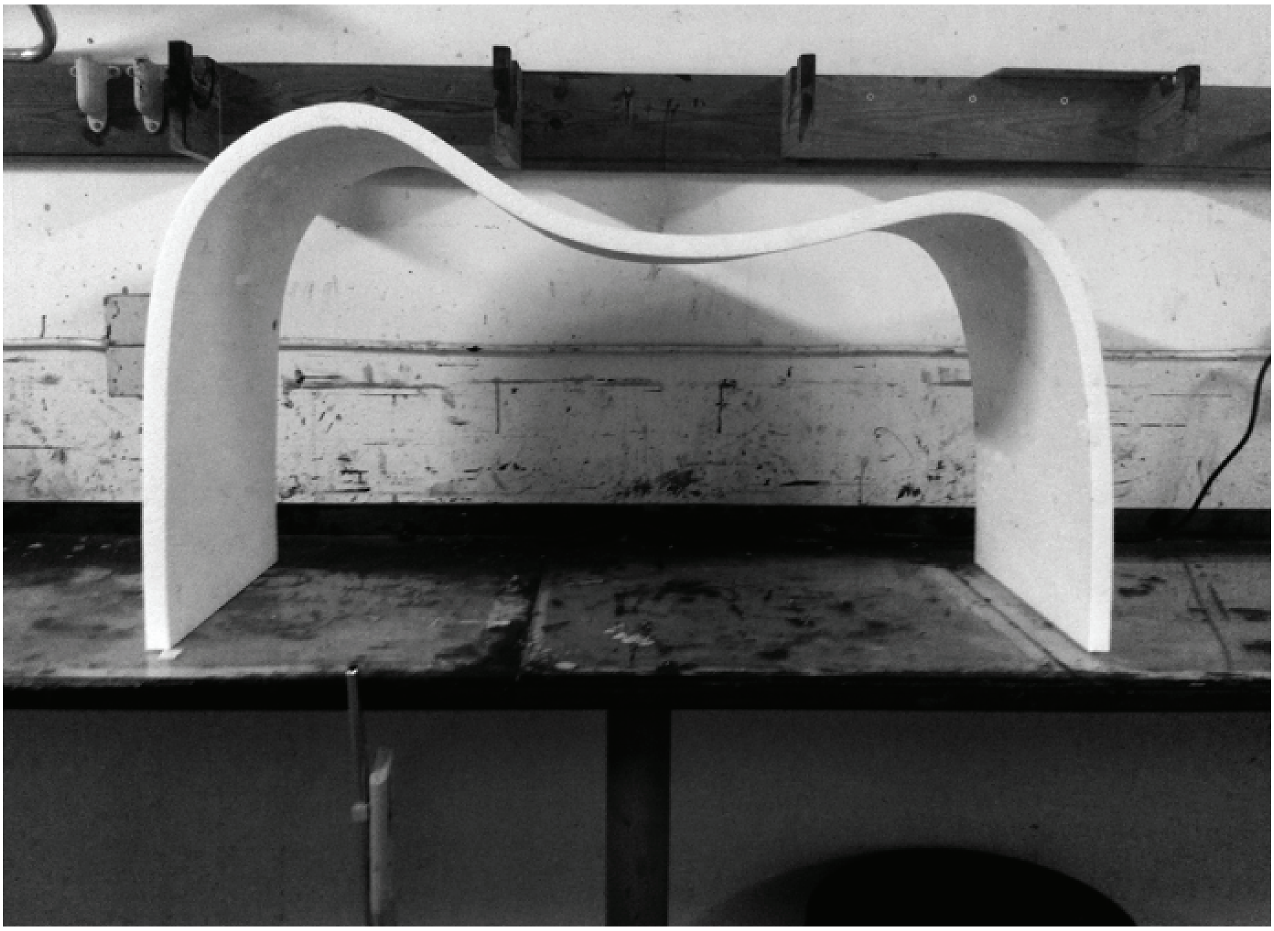


Figure 045. Foam cut prototype of the developed form.

The form was evaluted through 1:1 models. Figure 045 shows the final form. What was appriciated about this form was that it was one surface, and this would give more focus to the textile pattern. The form does not need connections, as opposed to the last form. This also moves more focus to the surface structure and pattern

In the analysis and in the physical model it was noted that the legs tended to slide out and compromise the structure. Different solutions was discussed. A tensions chord could be added, but needs to be attached and would also take focus from the aim. It was decided the problem may be solved by a silicon strip, that would enhance the friction towrds the flooring material.

11.3 ANALYSIS

The analysis was carried out using an isotropic, linear elastic material with loading in the form of an eliptic pressure on the seating area. The shape was imported from 3D-modelling program Rhinoceros and analyzed in Ansys FE-simulation program. We looked at the stress vectors and stress concentrations. To verify the model we also studied the deformation figure.

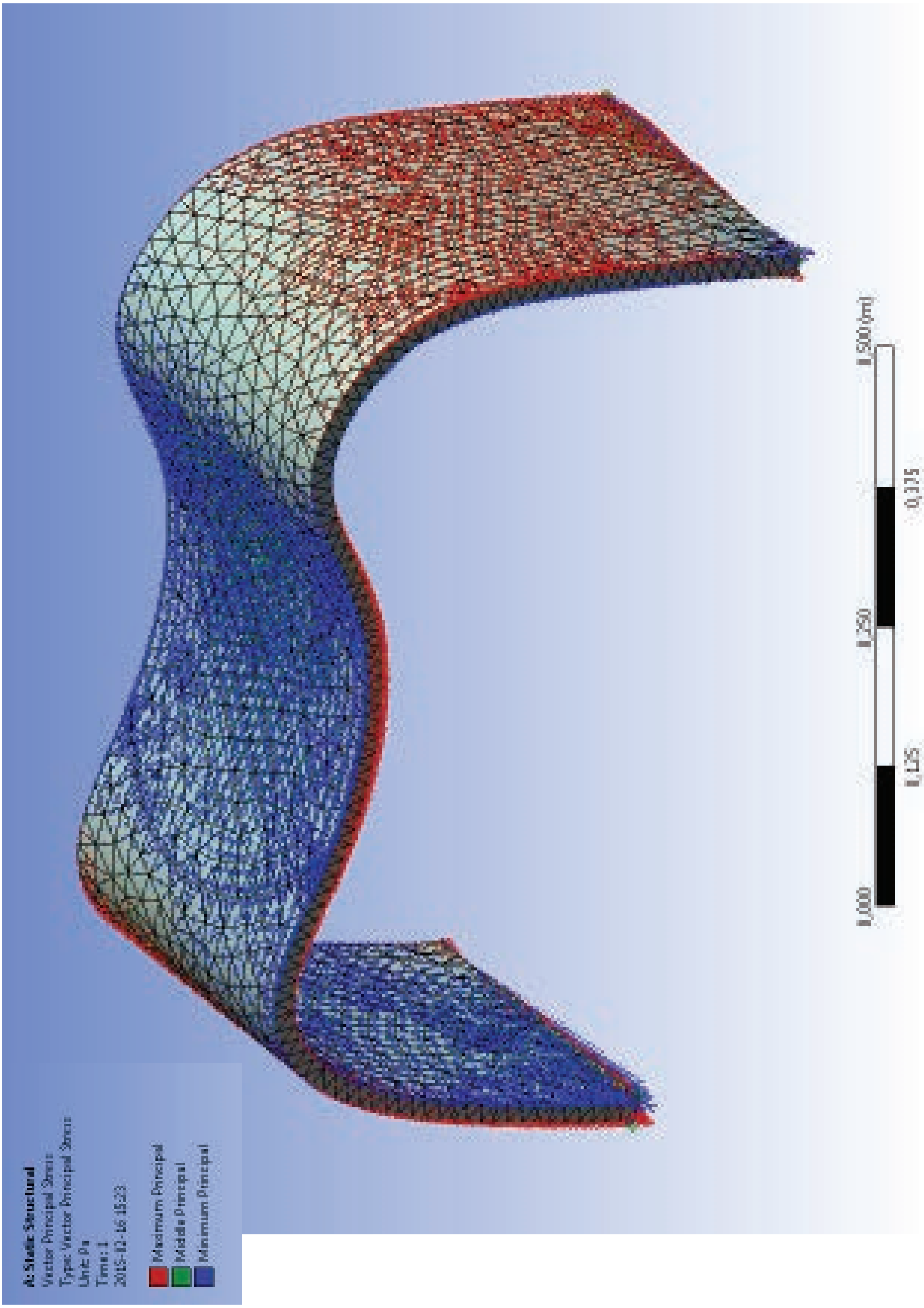


Figure 046. FE-analysis of the form showing principle stresses as vectors.

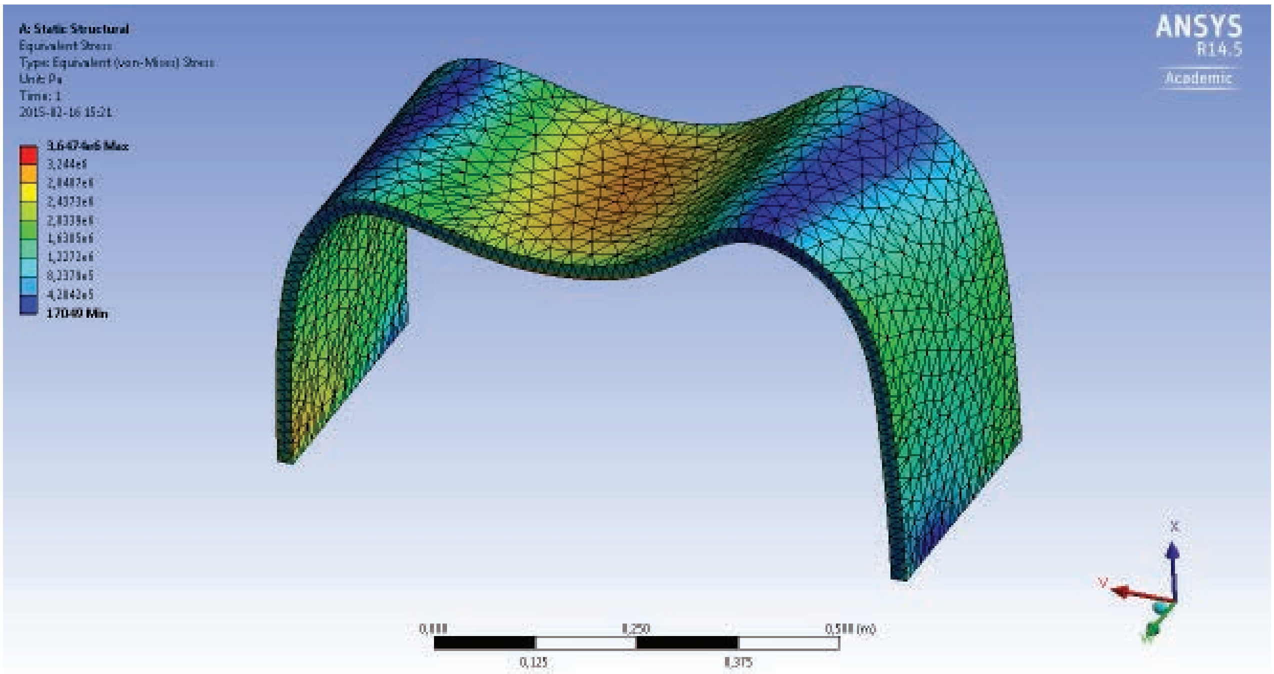


Figure 047.FE-analysis of the form showing equivalent stress (von Mises).

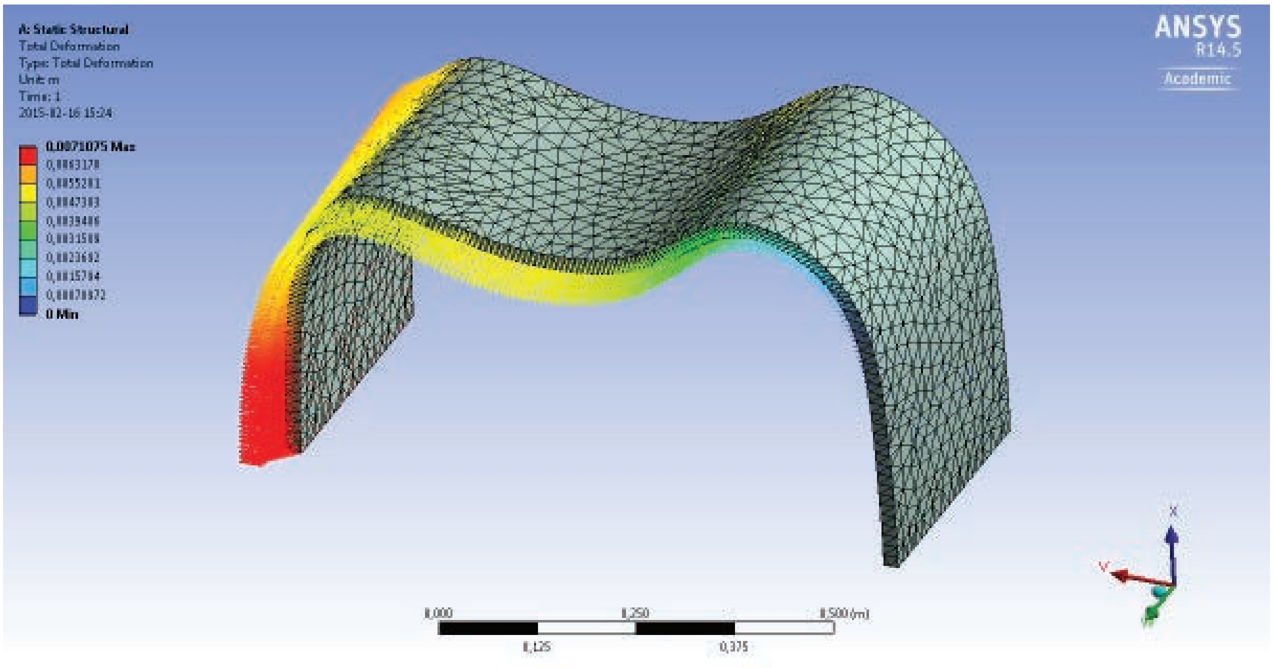


Figure 048. Deformation of the structure.

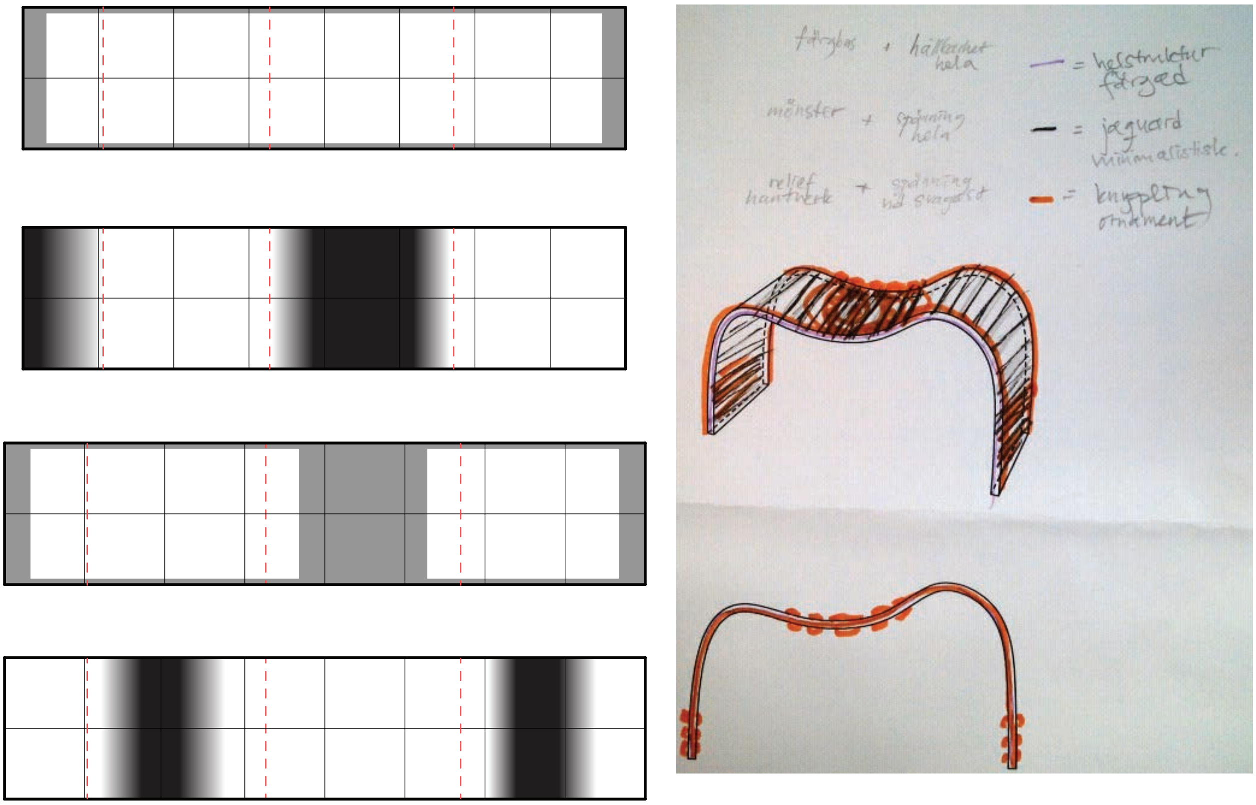


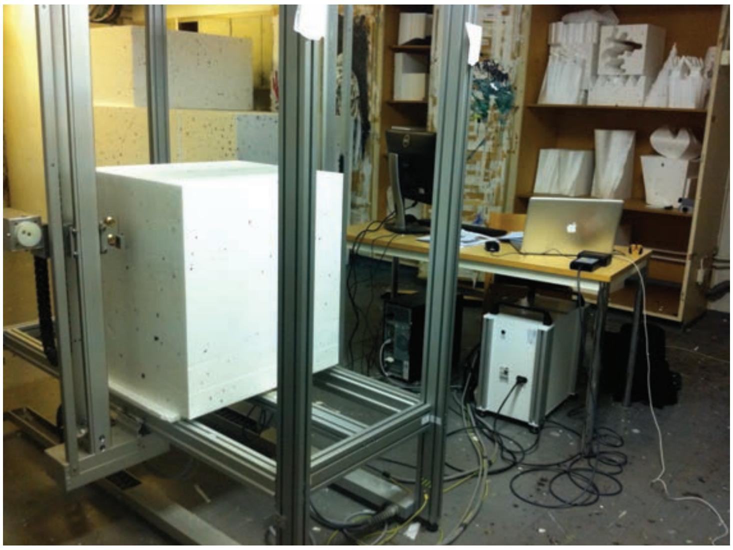
Figure 049. The strengthened brim and the tensile stresses (black), for the underside and topside. The red dotted line shows he transition zone between tensile and compressive strength well suited for possible seams.

From the analysis we made a pattern that would inform the textile design. For Prototype one we used figure 049 right, and was made before we had time to carry out the full FE-analysis. Prototype one was carried out prior to FE-analysis. Figure 049 left shows the informed pattern. In gradient black we see the areas affected by dominant tension stresses, and where the textile reinforecment is needed. The red dotted lines indicate points were seams and edges may be placed, since stresses are small here. The light grey areas are the intuition based addition, giving a stiffening frame and a reinforced seat.

12 PROTOTYPE MANUFACTURE WITH SHAPED TOOL

12.1 MANUFACTURING THE TOOL

To manufacture the designed shape we needed a tool, or form-work, in the designed shape. We had access to an EPS cutting robot through Chalmers A-verkstaden and decided to try and use this for our tool.



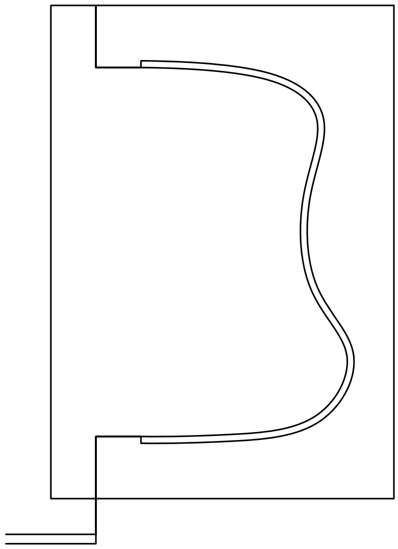


Figure 050. A computer numerically controlled (CNC) hot wire cuts the EPS foam according to digital curves exported to a dwg-format. To the left the machine, to the right an illustration of the cut-file.

An issue with having an EPS form work is that unlike the aluminum sheets used before, it is not vapour tight. Several tests where made to find a solution to seal the tool. In a production situation the form would have been CNC milled from a piece of aluminum or airtight foam, which our budget did not allow for.

Initially we tried sealing it with paint, an idea from Chalmers A-verkstaden, but this proved insufficient. We tried forming a piece of plastic over the form, but without the possibility to heat the whole plastic at once this did not work.

After this we tried coating it with polyurethane, which worked great but is hazardous and difficult to work with outside the fume cupboard, due to its toxic fumes and very short hardening time (less than 2 minutes from mixing, in room temperature).

Next we tried coating the EPS tool with aluminum foil, glued onto an EPS surface with epoxy, but this was too fragile and easily broken during both set up and injection.

We then tried again the idea of using the epoxy as glue but this time attaching a sheet of PE-foil (already used in injection as top layer) and this became the method we continued to use. However, it was not perfect since the vacuum force was much stronger than the epoxy attaching the EPS to the foil, which led the foil loosening. This had consequences. One reason for choosing the bagging technique was the possibilities of having a relief surfaces, following the textile shapes. When the PE-foil released from the form, we had this effect also at the tool side of the sample. It meant that the whole bagging could give in to the wrinkling forces in the concave curvatures of the form, which it also did. So we where at some spots very exact along the form and at some places as far as centimeters from following the shape form-work.

Figure 051. Experiment with polyurethane.

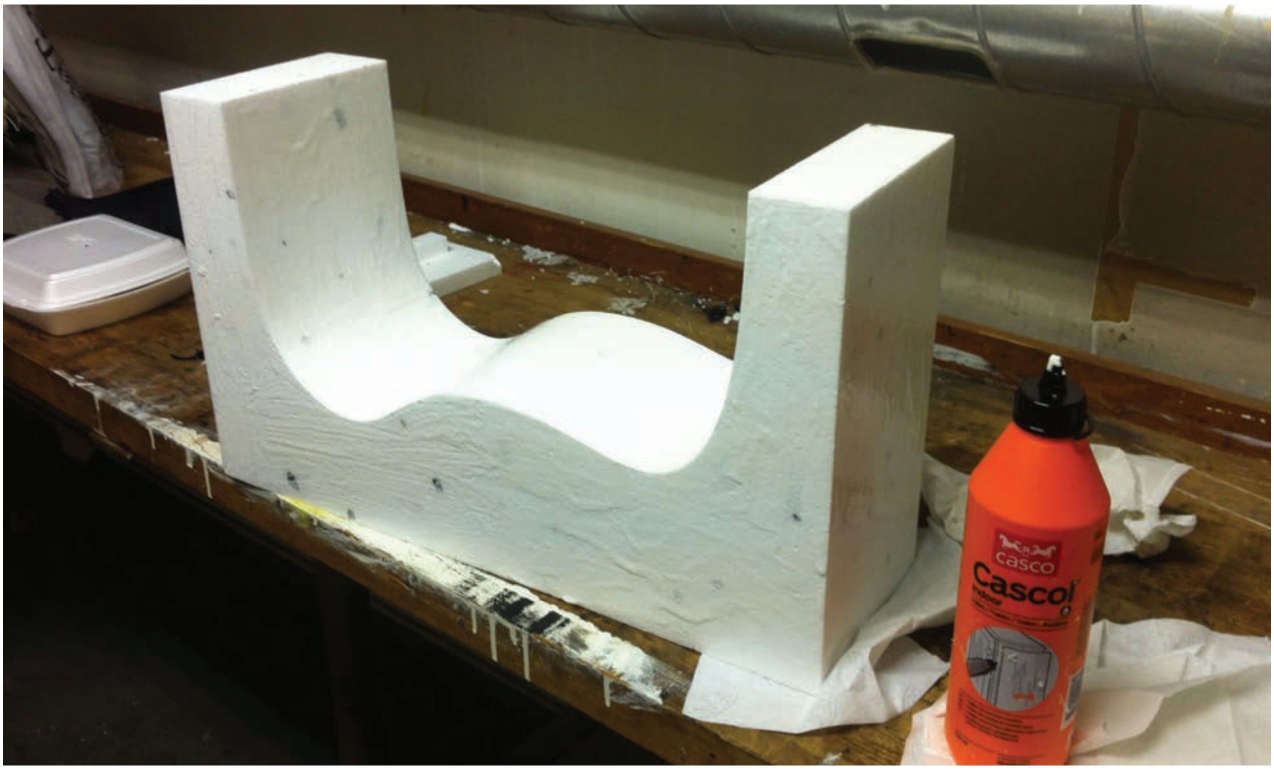


Figure 052. Experiment with white glue.

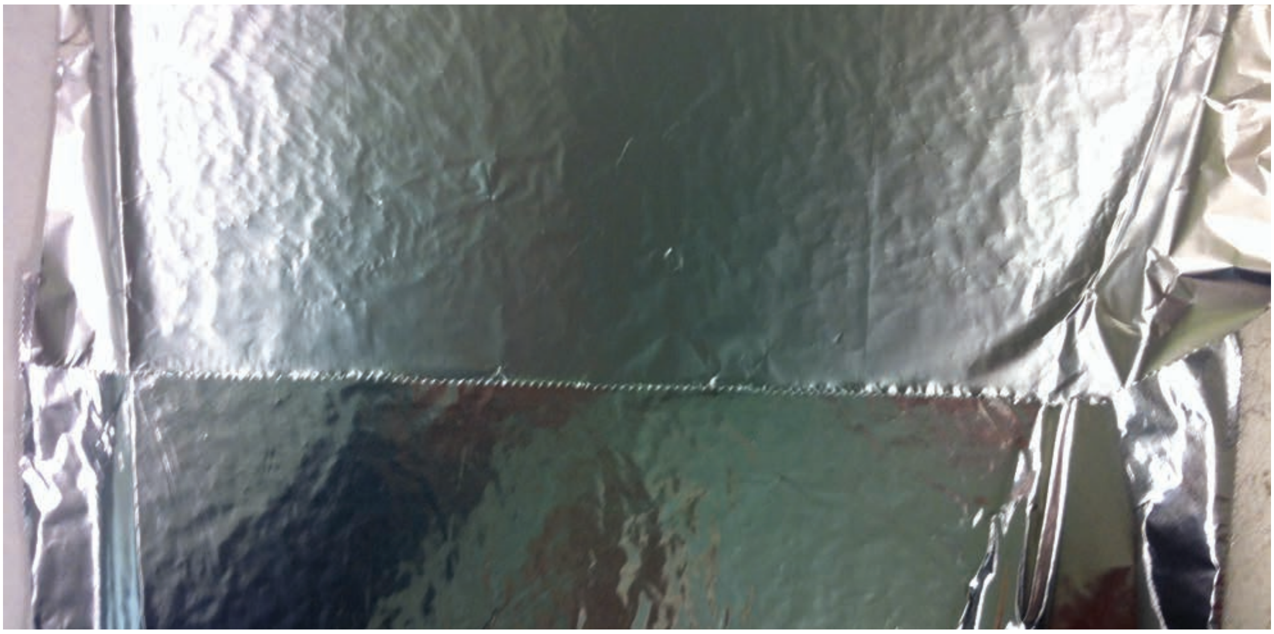


Figure 053. Experiment with aluminum foil and epoxy.

12.2TEXTILE SAMPLES

In this first laboratory with a custom tool we explored possibilities with the textile technique braiding. The composite was built up from eight layers of plain weave flax textile. The weaves was ordered from the France based company Composites Evolution who is specialized in bio textiles for composites. The difference between a standard flax weave and the ones designed for composite applications is that the fibres are separated and selected to get a more homogeneous fibre base to spin treads from. The strongest and weakest fibres are removed so the weave have less dispersion in properties.

The braided textiles tested were one braided mat of sole wool yarn, not died. The other was a thick wool yarn dark brown base with additions of specially made braids consisting of wool and flax fibres around a Kevlar core. We aimed to investigate the appearance of the yarns and braids as infused with epoxy as well as the appearance of the relief pattern formed by the knots in the textiles. We placed the textiles in the curved part of the tool and on both sides of the flax layers to see the two results.

Figure 054. Left: Textile sample before infusion. Right: Fabric samples of the flax core layers.

12.3 INJECTION PROCESS

The production method we had decided on already from our first sample test was injection molding. Since the process can give a result that varies in thickness for long injections we injected from the short side and with a diagonal placement of the source of resin and the vacuum pump, figure XX. The epoxy used was 'NM Infusion 664' mixed with 'NM Härdare 650' (hardening) at a ratio of 100:35 (weight).
Our set up:

1. Tool (EPS)
2. Epoxy glue
3. PE-foil
4. Braids
5. 8 layers of plain flax weave
6. Braids
7. PE-foil

We used small diameter tubing along the long sides of the tool and air tightened the bag with tacky tape.

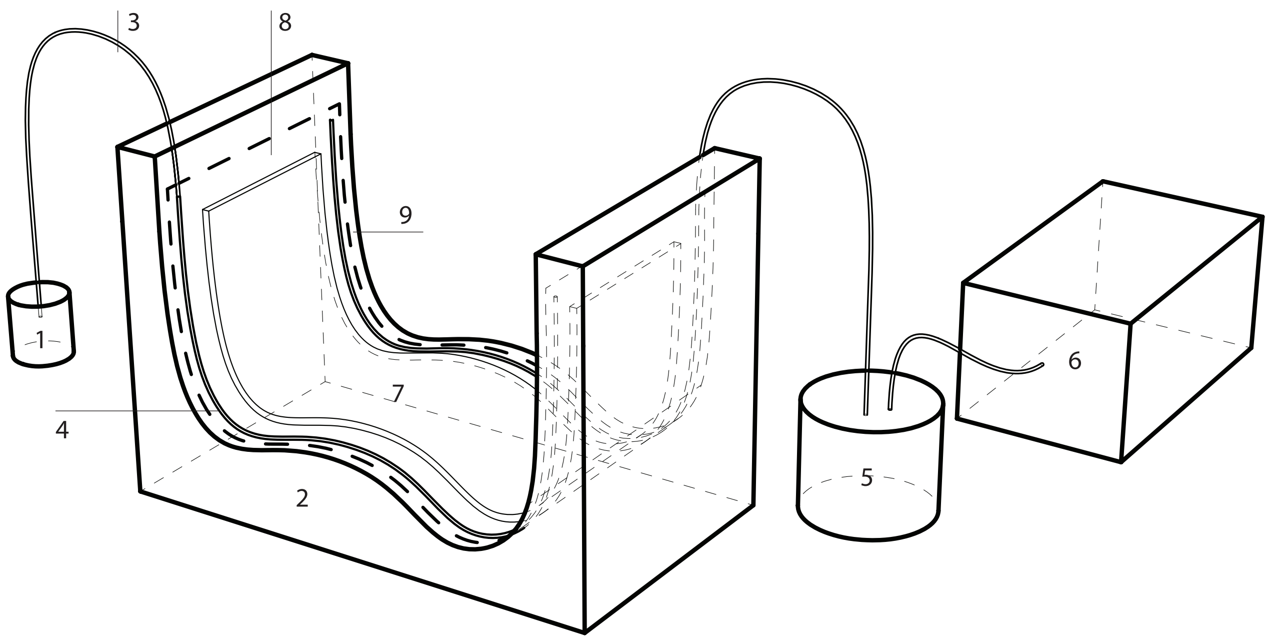


Figure 055. Set up. 1. Epoxy container 2. Tool 3. Tubing 4. Slit tubing 5. Trap 6. Vacuum pump 7. Textile layers 8. PE-foil and 9. Tacky tape along the sides

The first time setting up gave us a few problems to solve. We chose to use the negative side of the form to get an even surface on top. This meant that the textile during the set up would slide down from the legs of the chair, or side of the tool. This time we made a quick solution with duct tape and then sawed off a part of the leg. We had also cut the excess too narrow so it was very tight to place and fixing tubing which forced us to make a smaller piece than what we had intended. As mentioned earlier, the PE-foil did not attach well enough to the EPS and caused the tool side to wrinkle and wobble in shape.

Figure 056. Therese is fixing the tubing to the tool and putting a protective layer of GF-weave around the tubes, in order to not puncture the bag with sharp edges. It is also important to add the GF-weave to distribute the vacuum between the tubing and the laminate layers.

Figure 057. Samples of different types of flax weave. The braided textiles, to the left the coarse yarn with special braided strings and to the right medium sized wool yarn, before injection of epoxy.

The epoxy and hardener was mixed in a fume cupboard, the whole volume at once. The mixing was done manually. We tried to mix it well but without stirring down too many air bubbles, however this was not entirely possible. During injection we noted that the porous wool yarns acted as distributors of epoxy, they were wetted first, and improved the distribution to surrounding flax weaves.

The injection took two hours, after which the epoxy cured in the pot and tubes. The composite was not fully wetted at this point.

Figure 058. The injection is done and we check the temperature of the laminate to see if it has started to cure. When the curing is well under way the vacuum pump can be turned off.

12.4 RESULT

The injection partly failed. The suction from the vacuum pump and the surface tension was not enough to drive the epoxy all the way up the leg on the side farthest from the epoxy inlet. From this we learned that it could be beneficial to have some extra tubing so the inlet and outlet positions can be switched during injection. The tubing diameter may also have been on the small side, but this usually has little effect. Another possible reason is that the pot life of the epoxy was reduced due to mixing too much at once. It is better to mix little by little since the increase in temperature due to the curing epoxy accelerates the curing of the entire pot.

Figure 059. Result images.

The results were not measured for strength but were surface hard and form stiff. There were some air bubbles trapped in the wool. Normally air bubbles are, to some extent, drawn out from the epoxy by the vacuum pump. Here it appeared that more than the normal amount was left in the composite due to the wool.

Figure 060. Peter Hellström helps us to remove the PE-foil from the piece. The epoxy is now cured and there is no risk in working without gloves or other protection. Care must be taken as not to get tacky tape on the laminate, since it takes a lot of acetone to remove it.

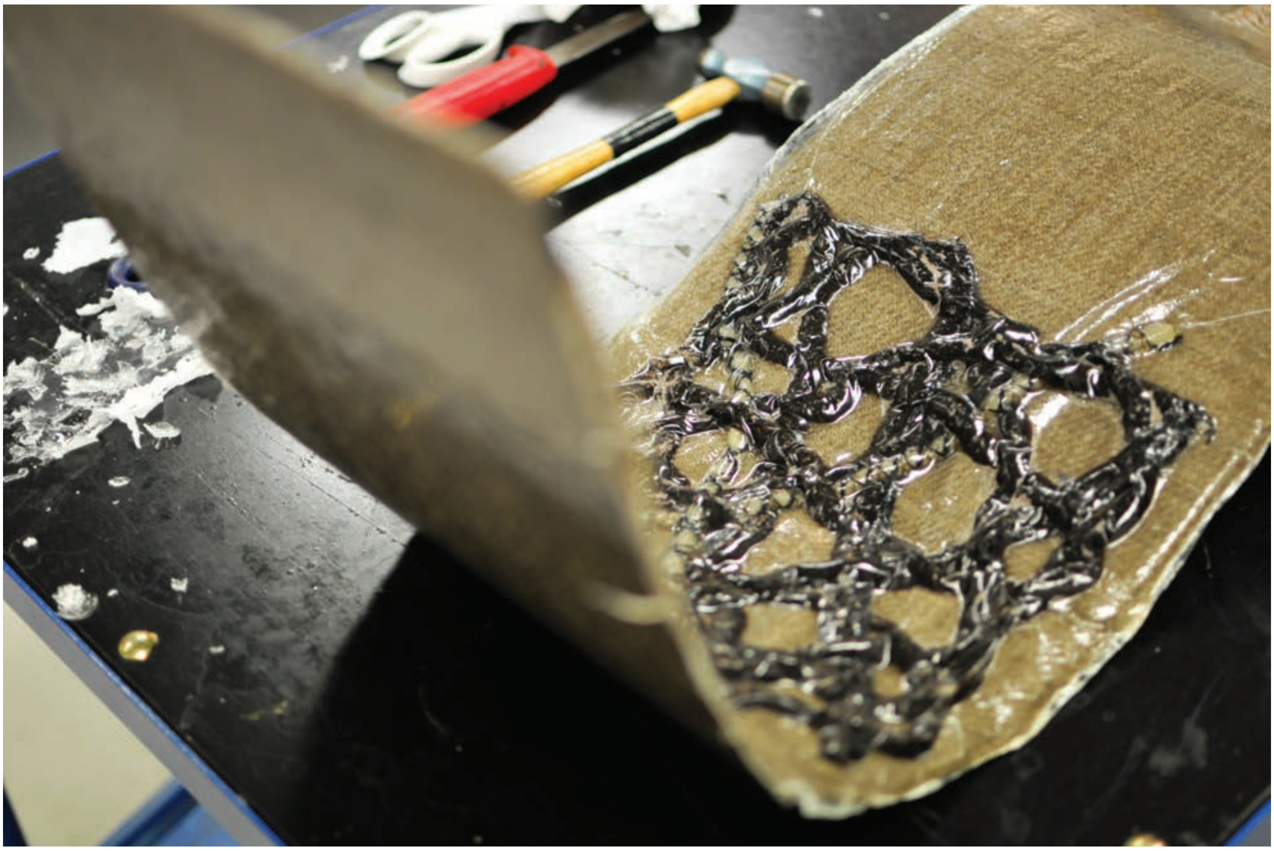


Figure 061. Result. The shape is closely met on most places. Folds and wrinkles in the PE-foil are clearly visible in the laminate.

A very clear change in colour occurred due to the injection. The change in colour is almost the same as when a cloth is soaked in water. The difference here is a slight coloration to the yellow, something which will increase over time and with UV-light exposure. The PE-foil bagging rendered the surfaces highly shiny and with a sort of slimy appearance that was not very appealing.

Figure 062. The top side result. The surface towards the foil is very shiny and has an almost slimy appeal. The part where the brown yarn is more sand coloured is due to air bubbles.

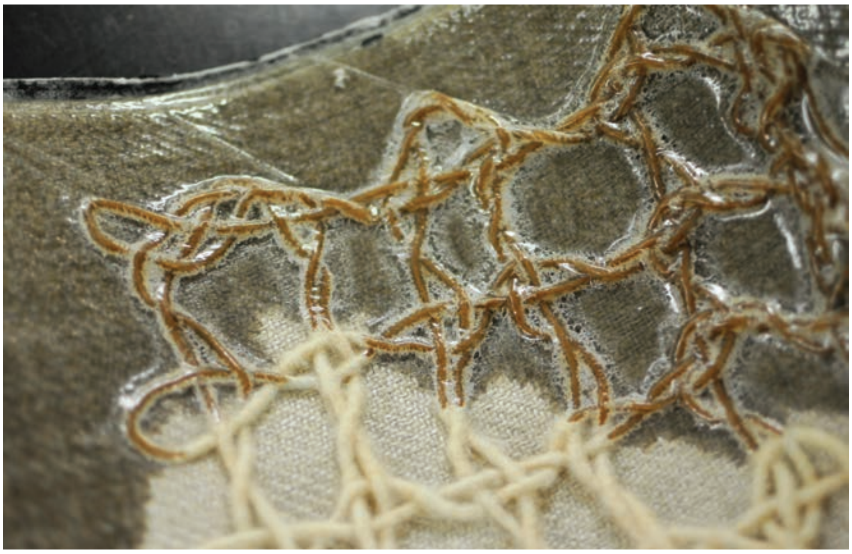


Figure 063. Sample test.

Figure 064. Detail image of the tool side. It is easy to see which part of the tool side released from the form and which did not. Where it released, the relief is as defined as on the open side of the tool.

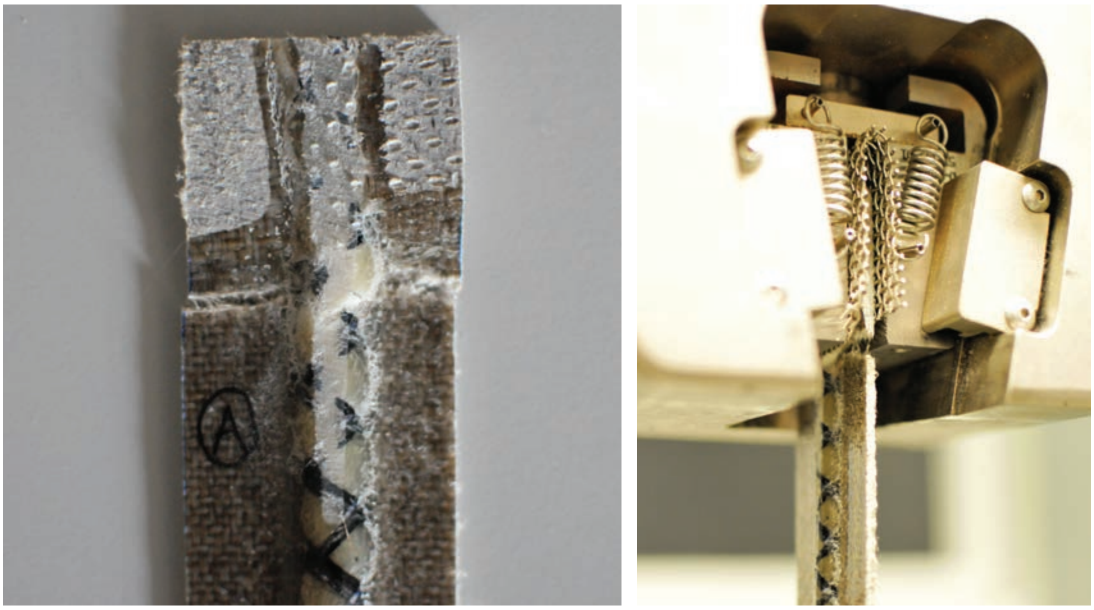


Figure 065. Left: Tested sample. Right: Clamping the test sample with steel grid.

We tried to make samples and measure the strength through pulling tests. But the tests were not successful due to poorly manufactured samples. The idea was to test the different braids so a simulation of the chair could be carried out.

12.5 RESULTS IN DETAIL

12.5.1 POLISHED CUT OUTS

After viewing and documenting the results from prototype samples we saw out interesting parts and polished these to get a better idea regarding the structure and quality of the material. We also looked for potential detailing of the final chair prototype.

Figure 066. Cut out and polished part of the prototype sample.

In figure 066 we see a polished sample where the underside has been towards the tool and are therefor flat while the upper side has been free and is relief. The eight layers of textile are clearly deformed around the coarse yarn on the tool side. We can also note that the wool yarns have a large ratio of resin in them. In composite you generally aim for a high volume to resin ratio as this gives a stronger laminate. We can therefor see from this test that not only is wool a weak fibre in comparison to flax or jute, but it also generates a low fibre to resin ratio. It may even be that measuring strength per weight ratio adding the wool yarns may have weakened the sample.

The yellow coloration from the epoxy resin is visible in the white yarn.

Figure 067. Cut out and polished part of prototype 0.

We see in figure 067, which shows the tool side, that a crossing between two large yarns create an empty space around it that is filled with resin. On this piece we also see large bubbles and even holes. Looking closely it is noted that the brown flax thread around the white wool yarn bleeds colour onto the yarn in the process. We also note that the white cotton yarn around the dark wool is shifting towards blue, which is interesting since other white tones turn yellow.

12.5.2 MICROSCOPIC FIBRE IMAGES

The braids produced by Therese Amus Gidlöf for the braiding samples consist of several materials. The braids are spun around a core of either wool or Kevlar. Initially the project was entirely wool but learning about the wool fibres poor properties as a reinforcing fibre we introduced flax and Kevlar. The flax fibres worked well aesthetically with the non-dyed wool, but the yellow coloured Kevlar was only used as core materials where it would not be visible. The Kevlar was a suitable synthetic fibre since it is flexible as opposed to glass fibre or carbon fibre that are brittle.

On a microscopic level the differences between the fibres are large. The Kevlar fibres are smooth, the flax fibres more flaky and the wool fibres large and like the flax, have a flaky structure. The structure of the natural fibres may help adhesion to the resin, but natural fibres are also greasier which works in the opposite way.

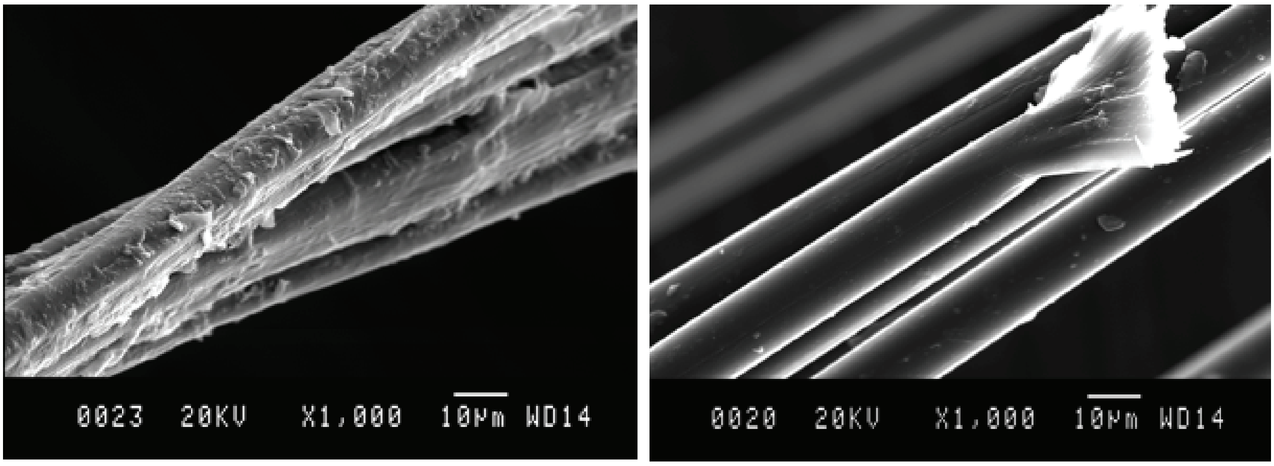


Figure 068. From left to right: Flax fibres at x1000 magnification. Kevlar fibres at x1000 magnification. Image taken with Flohultsmikroskåpet.

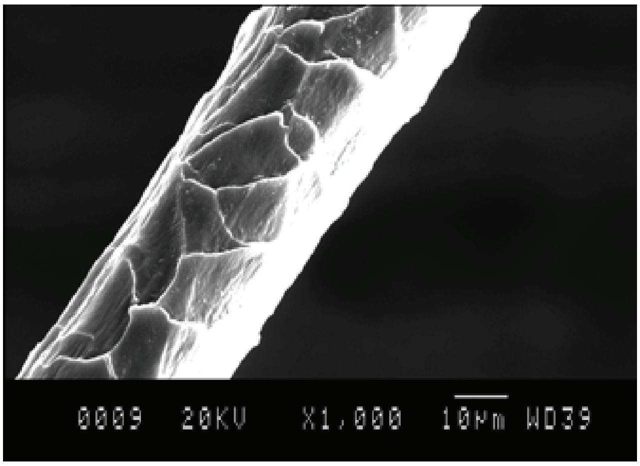


Figure 069. Wool fibre at x1000. Image taken with Flohultsmikroskåpet.

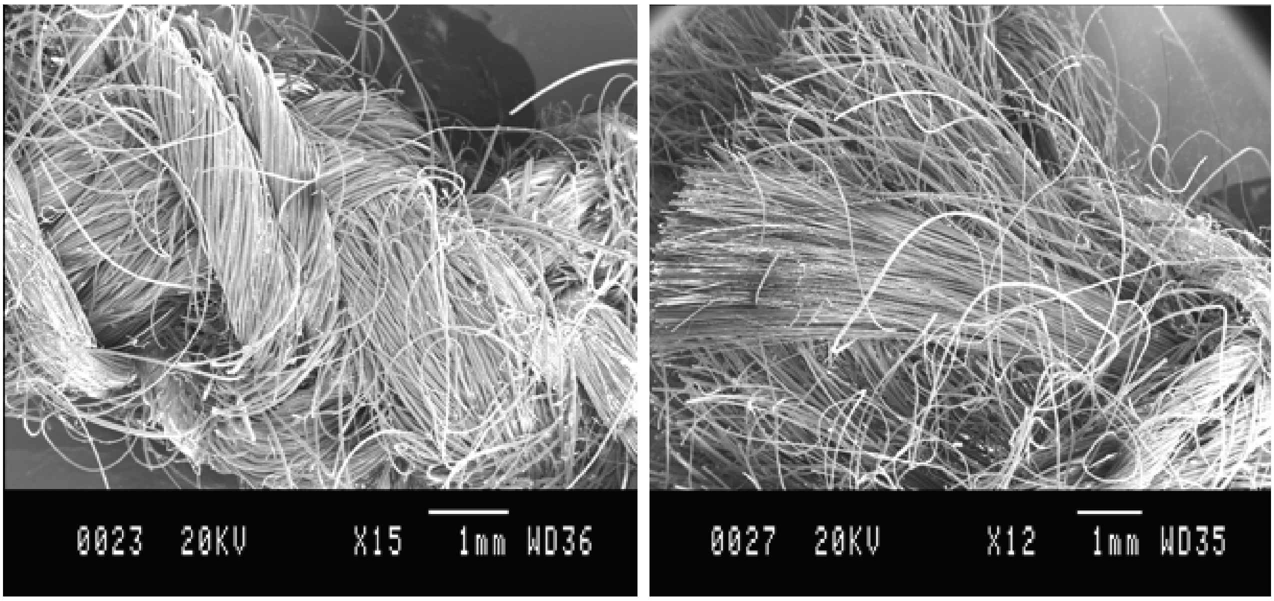


Figure 070. Images of braid with Kevlar core, wool and flax fibres around. Image taken with Flohultsmikroskåpet. Note the straight Kevlar fibres coming out of the braid in the right image.

Looking at the images it is easy to see that the wool fibres are sprawling. Direction of fibres is very important in fibre composites why this inexactness can cause loss of functionality.

We also compared the structure of the flax yarn in the special composite weaves and a regular yarn (figure 071).

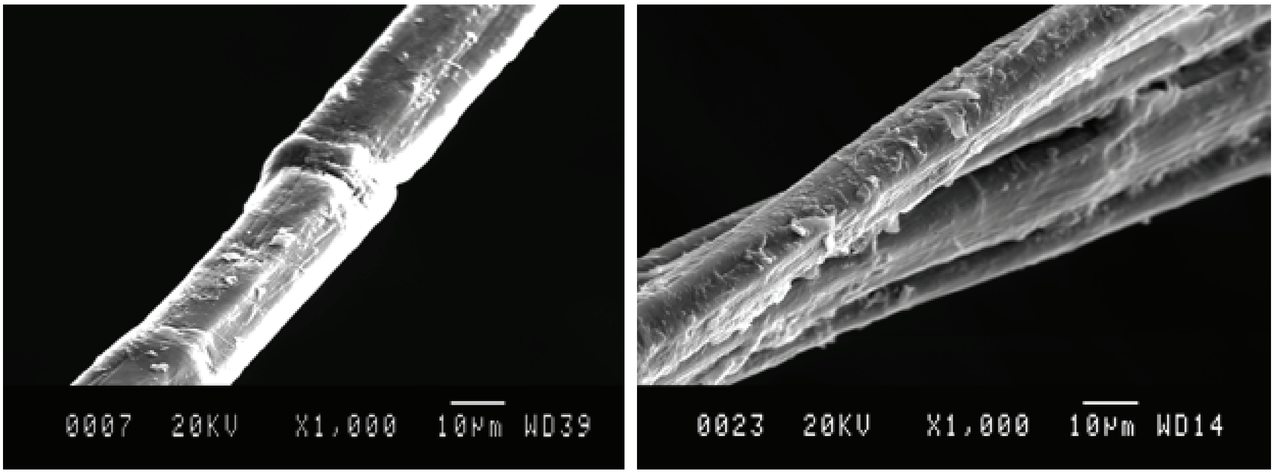


Image 071. From the left: Image of flax especially treated for composite applications, and image of regular flax yarn used for braids, Flohultsmikroskåpet.

It was hard to see any specific difference between the two. The difference in size between these two is not representative for the whole batch. Possibly could the slightly smoother surface indicate a more washed or treated fibre.

12.6 SUBSEQUENT SAMPLE IN THE SAME TOOL

We made one subsequent test reusing the same tool to test the result with a release weave. The weave is used as a layer between distribution weave and the laminate, but it also creates a matte surface we wanted to try. The result seemed promising and we continued with the matte surfaces.

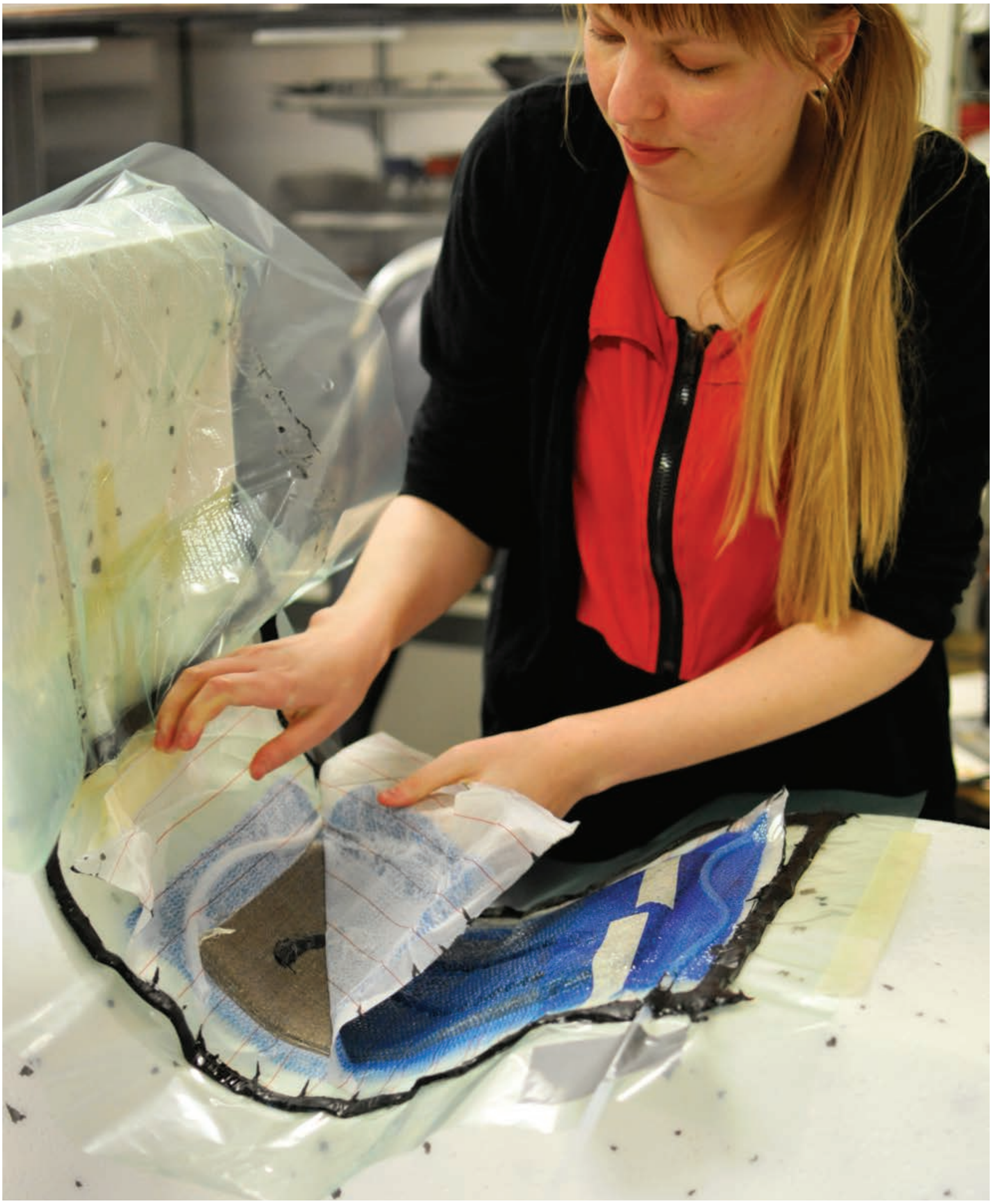


Figure 072. Sample test.

Figure 073. Sample.

Figure 074. Sample.

13 PROTOTYPE ONE

After the test run with our shaped EPS-tool described in chapter 12, we manufactured the first complete, full-scale prototype. The new tool used for this prototype, Prototype one, was cut wider and longer to allow space for the tubing and other equipment that are fitted on the tool during the infusion process. To simplify the infusion process we used the positive shape of the form.

Special flax weaves of two qualities were used for the core layers. One weave was a plain 90/0 standard and the other a +45/-45. Fibres of different orientations handle different stresses in the lamina. A total of 15 core layers build the laminate. The top layer was a hand-crafted textile in braiding technique, as shown in the figures below.

Figure 075. Left: Testing the braided textile on the flax and comparing with previous sample. Right: Making small corrections to the layers on the tool.

The colours of the wool and flax yarns used in the braided textile were chosen with consideration of the colour of the core layers of flax weave. The idea was to contrast the plastic and modern texture and look of the plastic composite with the natural nuances of wool and flax fibres. We had the intention of making a bottom layer, but the labour intensive braiding technique did not allow for this.

The idea for the integration of textile design and structural behaviour was to have high density in distribution and strong materials where the deflection was large. We also applied long continuous braids of strong materials align to large tension forces. The braiding pattern was coarse and therefore the interaction with the structural analysis was limited to the principal features.


Figure 076. Detail of the braided textile before infusion.

Since the lay up of the laminate is without fibreglass or carbon fibres, we did not need gloves for this process. The lay up is illustrated in the image below. The final layers of distributing weave and PE-foil is shown in figure 077.

The last infusion was unsuccessful due to insufficient pressure for the vacuum to drag the epoxy through all the layers. To avoid this we used:

1) Larger diameter tubes
2) Extra tubing so the inlet and outlet positions could be changed
3) The positive form to have more "downhill" infusion
4) Inflow on top of the tool.
5) Mix small batches of epoxy

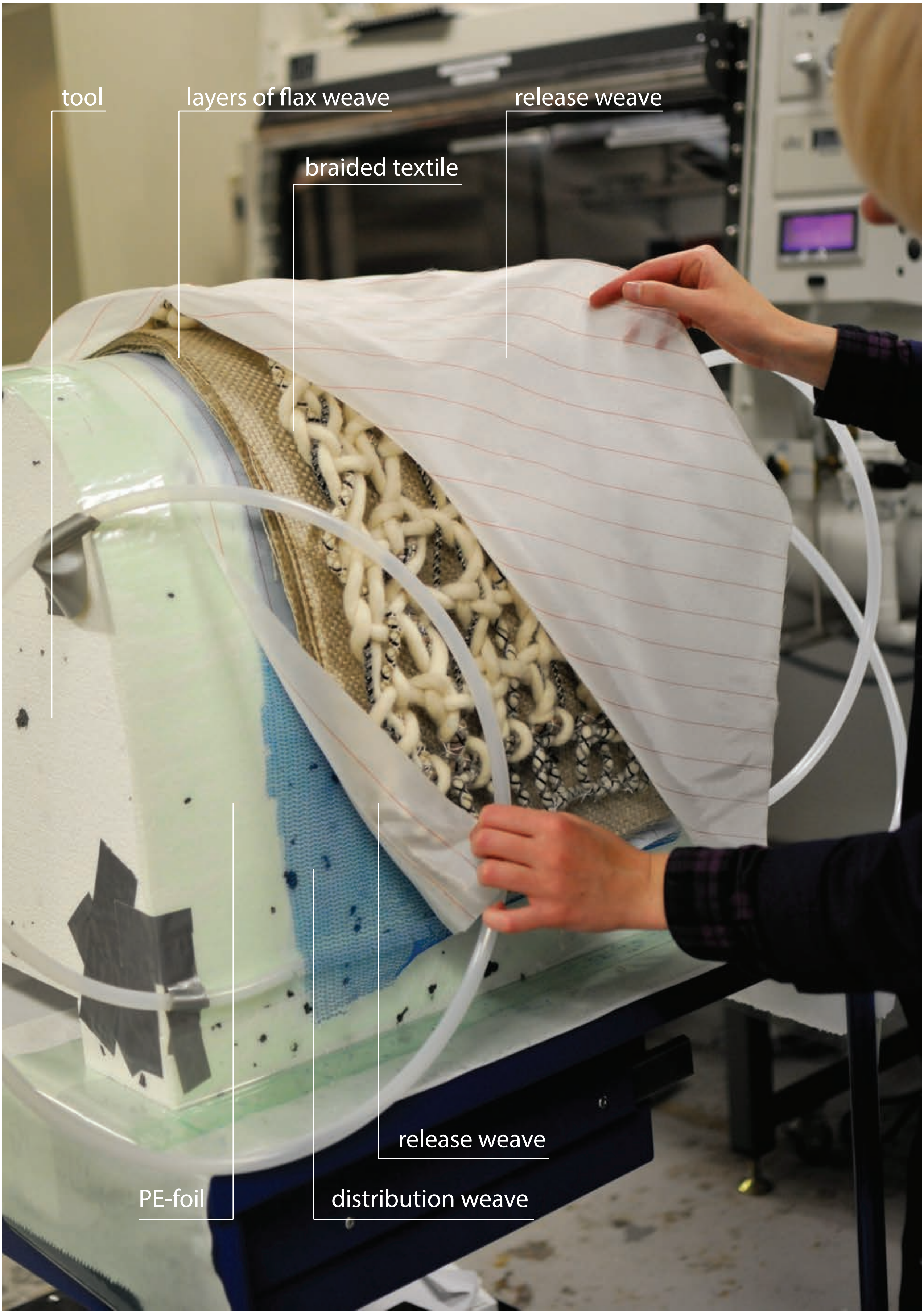


Figure 077. Set up of prototype one.

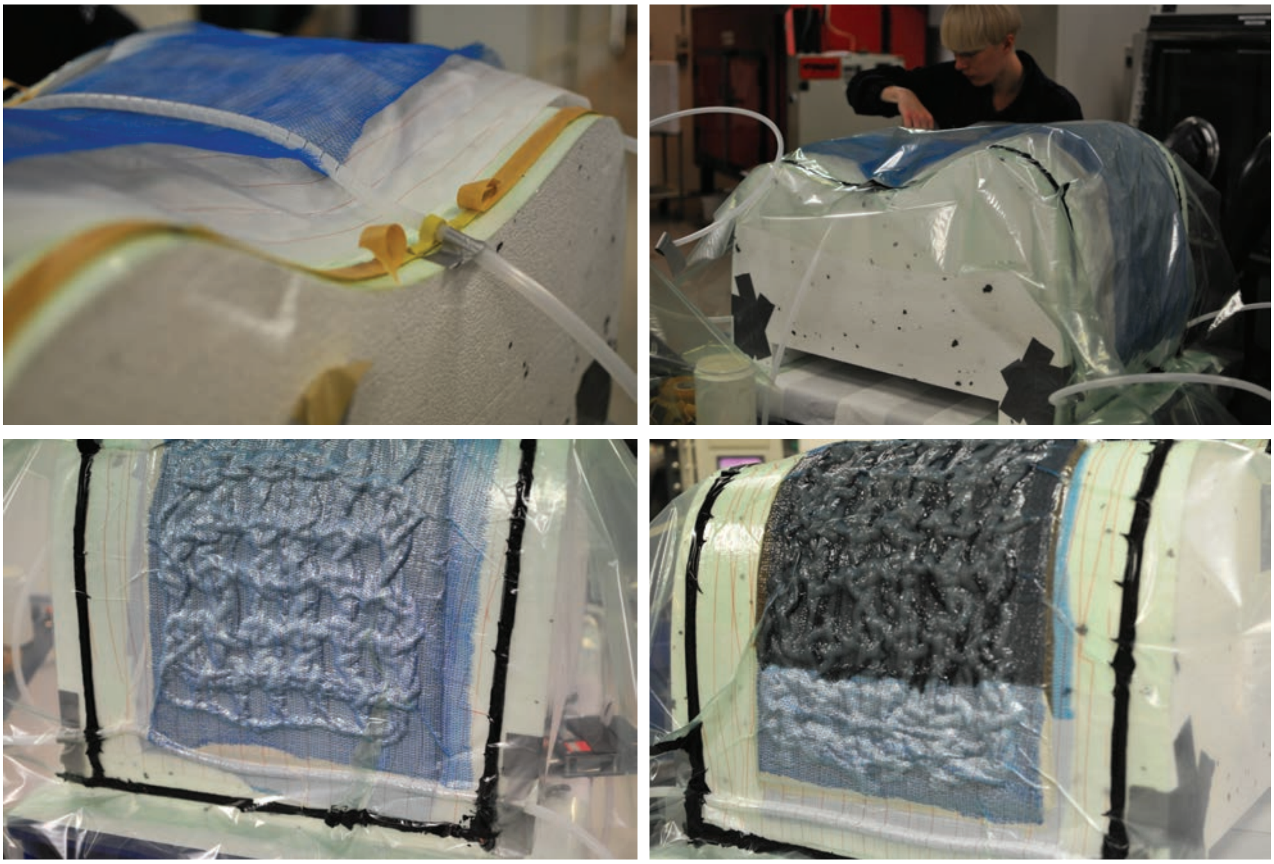


Figure 078. Top left: The inlet was placed on top of the tool. Top right: Adjustments when bag is in place. Bottom left: The vacuum is applied; small adjustments can be made to position of tubes and wrinkles in the laminate. Bottom right: The infusion under way.

The infusion went well even though it just turned completely wet when the epoxy began to harden. To keep track of the process the temperature of the laminate was continuously measured, over 34 °C means no flow of epoxy will go through this part. The smaller batches of epoxy prolonged pot life, but made it more stressful to handle. If the inflow runs dry it will start to suck air into the composite and make it weak and unusable. For the last part of the injection we used the extra tubing and switch the position of the inlet to ensure complete wetting.

Figure 079. Left: Measuring the temperature tells you how far along the hardening process are. Right: The vacuum pressure is measured and controlled at the trap.

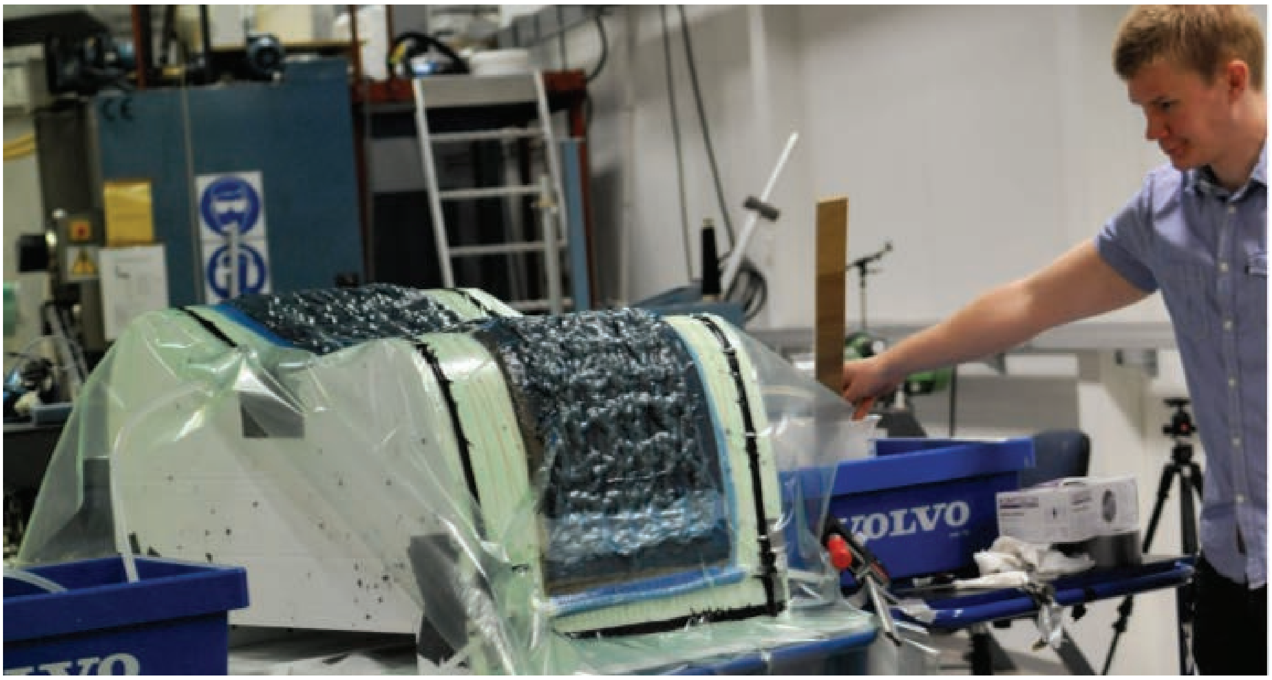


Figure 080. For the last part of the injection the inlet was switched to ensure complete wetting.

A large drawback from the set up was the inflow tubing on top of the tool. We had believed this would not leave a permanent mark, but it did as can be seen in figure 081. This was not beneficial to the aesthetic expression.

Figure 081. Detail view of the seating of the infused composite.

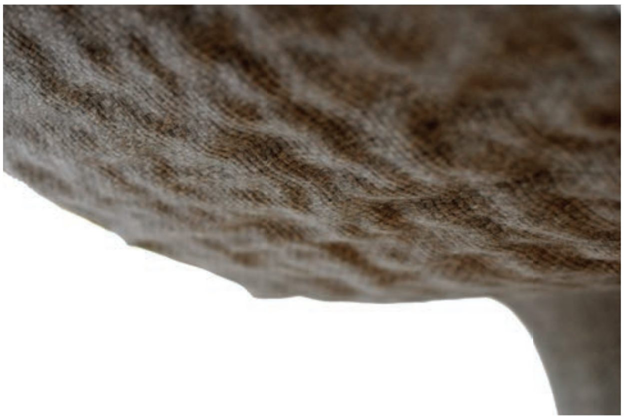


Figure 082. Detail image of the curvature.

As with the test prototype the PE-foil separated from the tool at several places. Where the PE-foil was attached the tool side surface was smooth, and where it detached the surface was bumpy. The bumpiness is due both the unevenness of the braided layer and the contractions in the foil due to the vacuum.

The edges were sanded to remove sharpness.

Figure 083. Detail picture of edge.

Figure 084. Prototype one as presented at EXIT14, at Swedish School of Textiles.

14 JACQUARD TECHNIQUES, PART TWO

14.1 LEARNING FROM JACQUARD TECHNIQUES PART ONE

In parallel to the braiding investigations the jacquard technique was further explored. The earlier jacquard patterns were inspired by braiding and faggoting. Those samples were homogeneous in the sense that the amount of material was the same everywhere on the weave. The pattern was just an image. Therese also manufactured samples with cutting technique from these jacquard weaves, but since the threads was cut off at short lengths it did not make sense as structural reinforcement.

Figure 085. Jacquard woven sample from our first tests. This piece shows the cutting technique and the floating weft.

14.2 ANALYSIS, COMMUNICATION AND PATTERN

Continuing to work with Form 2 and the analysis from that stage, we now developed our communication and integration of structural analysis and textile design. We drew a 2D-pattern based on the FE-analysis of the chair. We considered the tensile stresses, as can be seen in the figure below, were black represents large stresses fading into compression (white). We also used our best judgement and added a brim along the perimeter for handling unexpected forces. This was however not implemented in the textile interpretation.

The aim was to make a more continuous pattern where the threads would have a sufficient anchor length. Therese created the pattern below. The pattern to the left is for the top surface and the pattern to the right for the underside (this side is shorter due to the curvature of the chair).

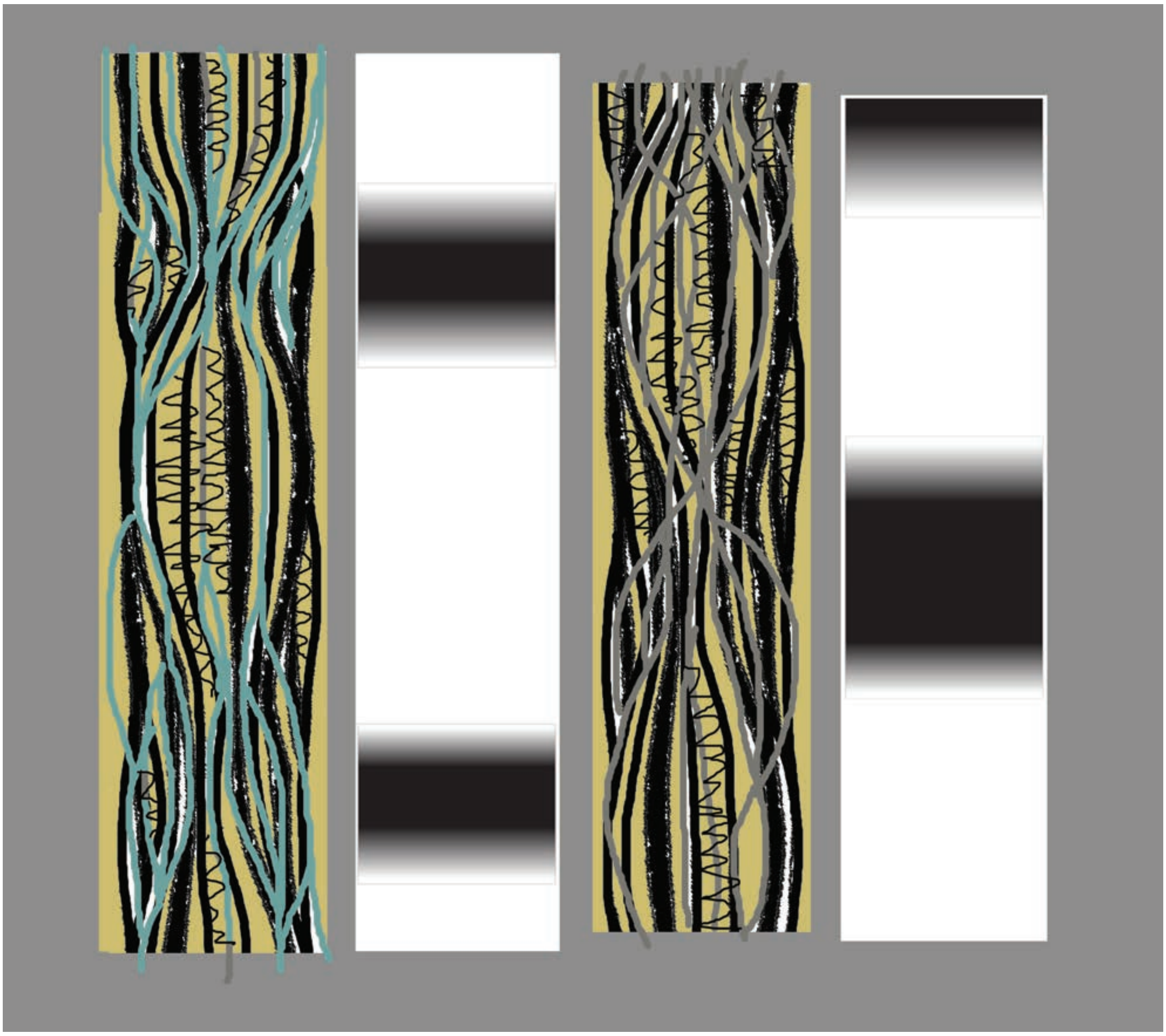


Figure 086. Textile design patterns and corresponding force concentration patterns.

The jacquard will look like a logical pattern, but in reality the continuous stroke of this design is woven with an orthogonal weave and the threads are still cut off. We also did not have the possibility to change the warp of the loom, which meant the weft is what the pattern is made of. The weft runs from left to right and not along the length of the textile, as would have been the logical direction.

15 PROTOTYPE TWO

For the second chair prototype we manufactured the form-work in the same way as for the first prototype, only larger to better fit all the distribution tubing, weaves and sealing tape needed during the epoxy injection. The textile was woven at Textil Högskolan on a jacquard weave with a white cotton warp and black wool weft. Knowing already before the injection that this was not going to be a path we would continue to investigate we made a thin chair with only five layers of flax in between the jacquard top and bottom.

Figure 087. The weave as it comes out of the loom.

Our layup

1. Closing the form-work with a layer of PE-foil attached with epoxy
2. Distribution net (blue)
3. Release weave
4. Jacquard textile layer (tool side)
5. 5 layers of plain weave flax
6. Jacquard textile layer (top side)
7. Release weave
8. Distribution net
9. PE-foil

We also used tacky tape, tubing, hose clamps for the tubing and you always need some duct tape. GF-weave around tubing.

Equipment used was vacuum pump, trap (closed aluminum container for surplus epoxy), plastic container for the epoxy, stick for stirring and a fume cupboard for the mixing procedure. You will also need approved plastic gloves and cover all skin in case there is and accident or dripping.
We used the epoxy NM Infusion 664 together with the hardener NM Härdare 650.

Image 088. Peter Hellström is removing the distribution net and release weave from the laminate. Even with the release film you need a large force. The dry wetting is seen to the right in the picture.

The injection was rather quick and easy with this thin layup. The vacuum pump was unfortunately needed else were and was removed prematurely. This caused the bagging to release from the layup and the epoxy distribution was not even, but we had large areas of dry wetting.

It would have been possible to re-inject the dry areas, but since we could already see this was a dead end this was not done.

The shape of the laminate closely resembled that of the form-work, but we still had a wrinkle on top of one convex shape, and the sombre appearance of the colours. The laminate darkened considerably during injection. The white threads of the warp almost disappeared in the black wool, which was elegant but unexpected.

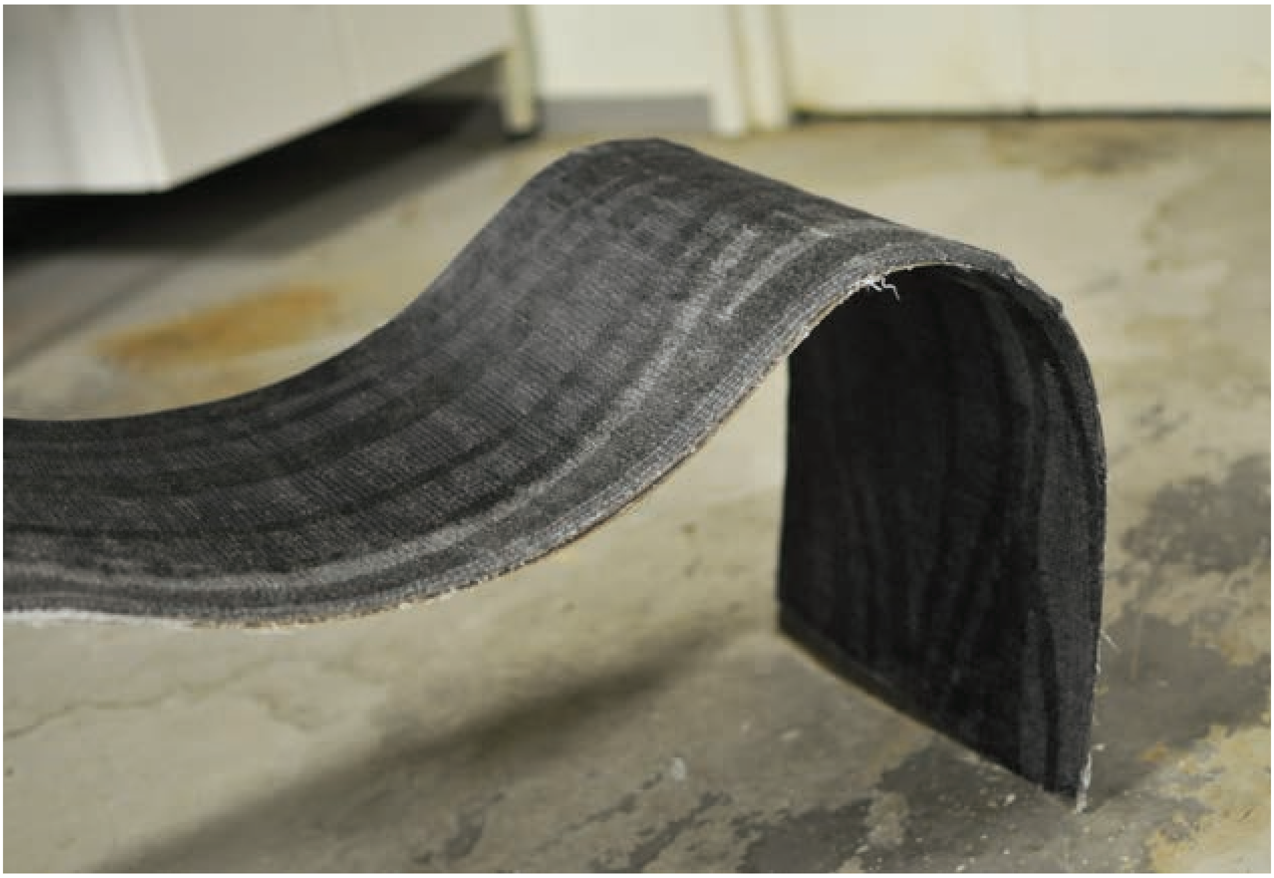


Figure 089. Result prototype 2.

Figure 090. Underside of the prototype. Visible wrinkle.

After the injection was made you usually post harden it through heating in an oven for 4-24h at 60-120C. This increases strength. Since this chair was thin and placed upright in the oven, the heating caused large deformations. A part of the chair was saw off to even it out. Since this prototype was not intended to be strong the heating process was unnecessary, but taught us that the laminate softens during heating and should be supported during this process.

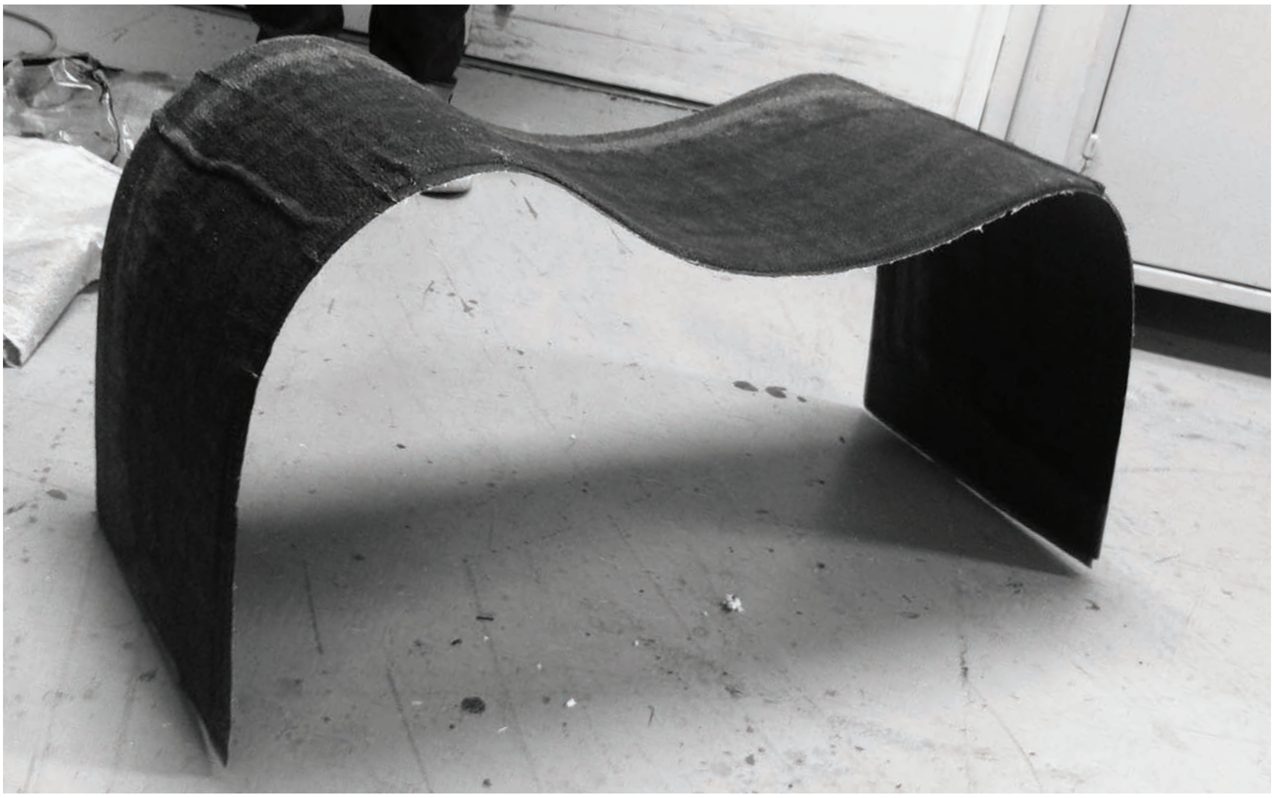


Figure 091. Result prototype 2.

16 FORM THREE

Since we experienced trouble with wrinkling of the material and air tight proofing the prototypes, we tried making a form that would pose fewer troubles and also to continue discovering new form possibilities and expressions.

16.1 FORM STUDIES

In the previous prototypes we experienced problems with wrinkles, predominantly on concave surfaces. We also felt that the form could be revised towards something slightly more efficient, in a structural sense.

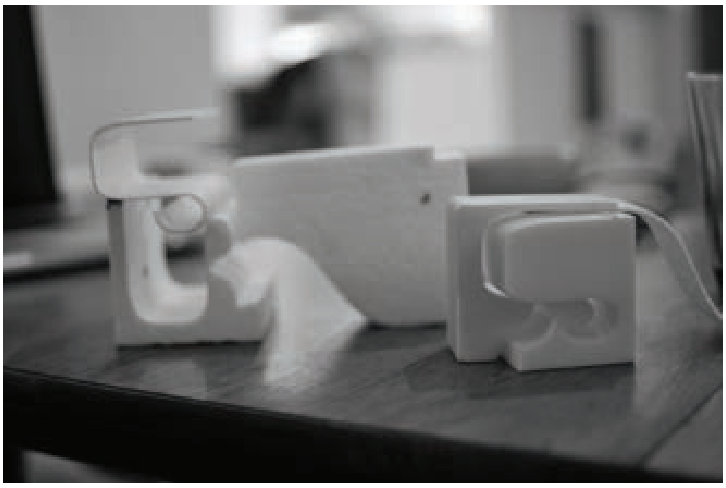


Figure 092. Shapes and form-work considered for Form 2.

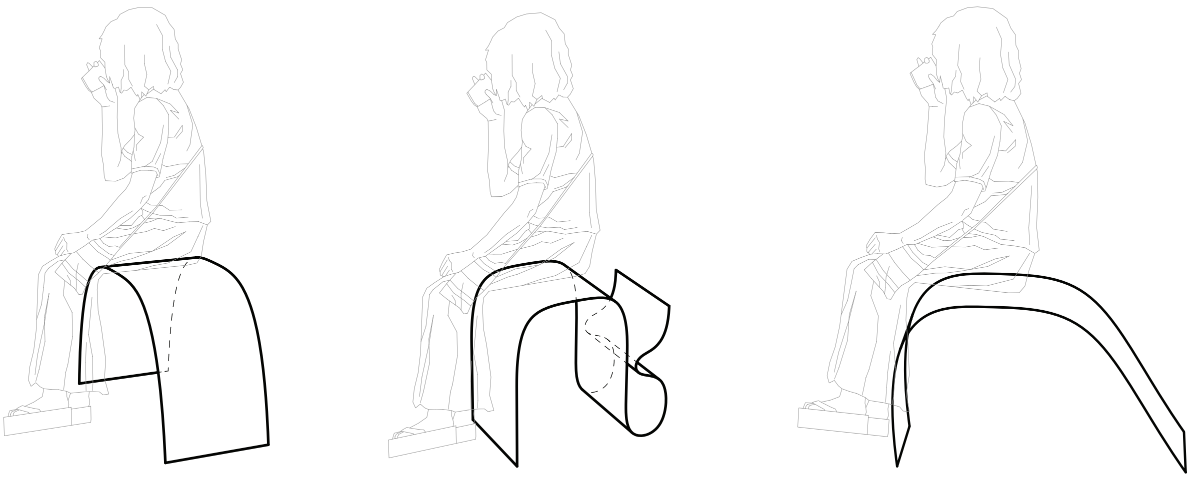


Figure 093. Shape studies.

There are many ways we could do this, but we tried an arch shaped form that would continue as a free form shape that would enhance that the textile could defy gravity when casted into epoxy. Several shapes were tested and some were too complex to manufacture with the tools available to us. Still, we felt that we had to try a new form since the old one had proved too hard to manufacture with a satisfying result in the laboratory.

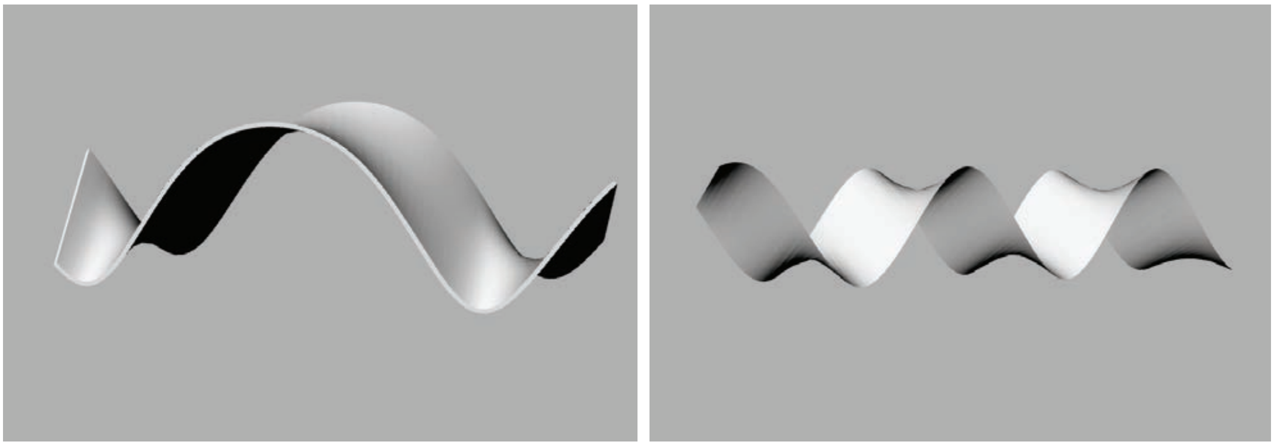


Figure 094. Form studies in 3D-modelling program Rhinoceros.

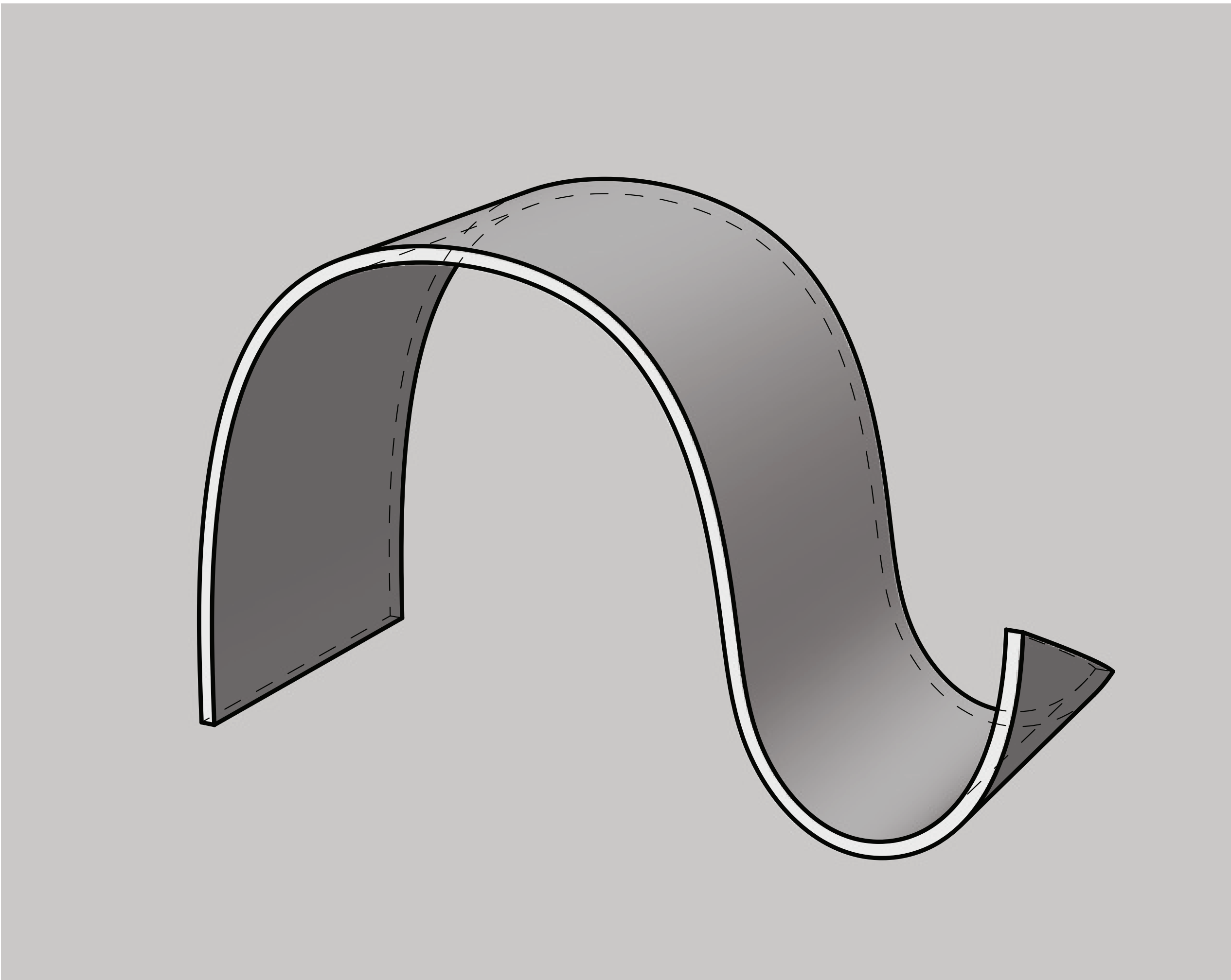


Figure 095. Chosen form.

Seen above and below is the shape we decided to elaborate on for our last full-scale prototype. It resembles the old one but has a super textile element of lifting the corner of the fabric, almost as if a hand did it.

For this form we tested a new textile technique – folding.

16.2 FE - ANALYSIS

The shape was modeled in Rhinoceros and imported into the FE-analysis software Ansys. The material was assumed isotropic and linear elastic. A pressure was applied on the top seating area and two fixed supports and one semi-sliding support. The boundary conidtions were respresented by one fixed allowing rotation, and the other support allowed a small movement in the horizontal x-direction. The composite surface is smooth creating little friction when placed on a floor, but we intended to place a small string of rubber underneath the curved support.

The FE-analysis of the generic material, with focus on stress distribution and direction, was the foundation for the textile design. Through examining the deformation behaviour and stress distribution at large, we could create a graphic pattern. This pattern is then be interpreted, as described in chapter 17.

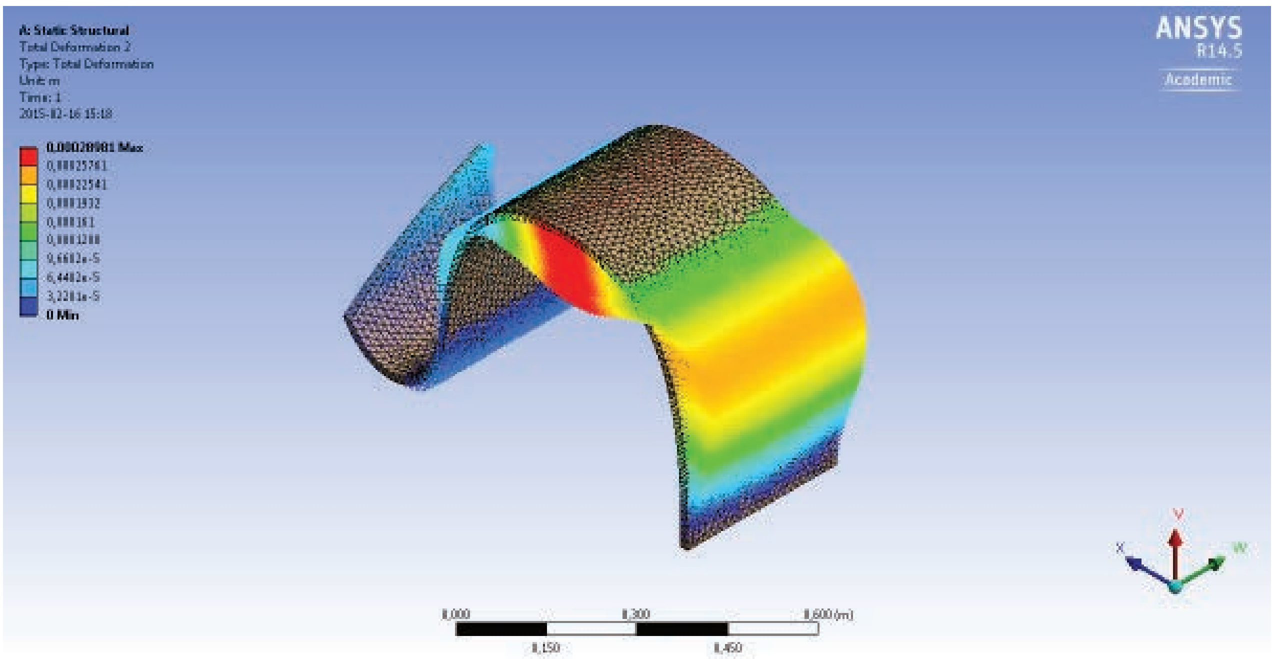


Figure 096. Principal deformation behavior, the scale of the deformation is relative and not actual.

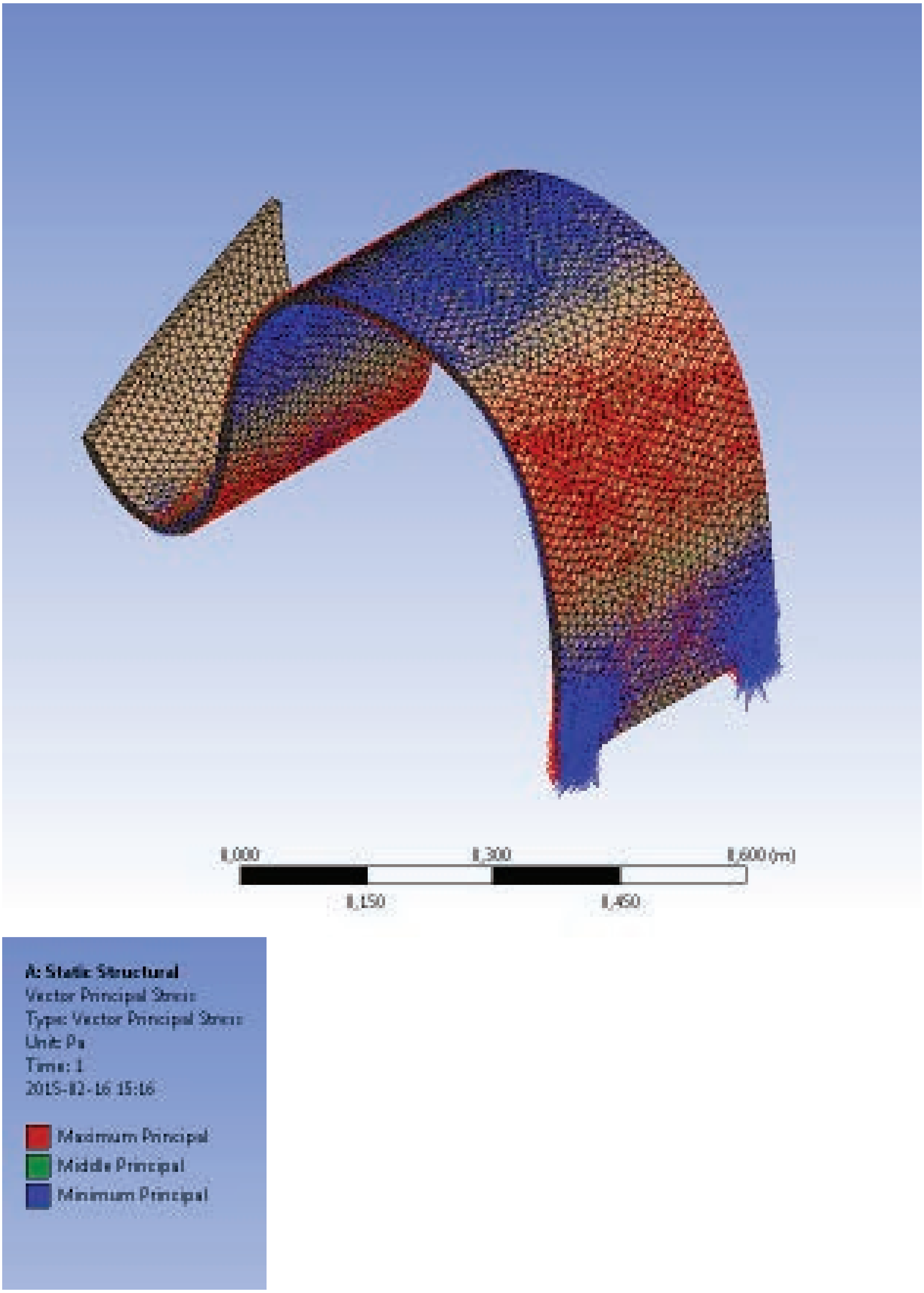


Figure 097. Principle stress vectors. Blue - compression, Red - tension.

17 FOLDING TECHNIQUES

17.1 POTENTIAL INTEGRATION BETWEEN ENGINEERING AND DESIGN

17.1.1 STRUCTURAL OPTIMIZATION, POSSIBILITIES OF VARIATION

Folding of a textile creates a local thickening of the structure and a fold can also change the fibre direction, locally or continuously after the fold. The first property is considered in this design. Thickening of a structure implies a greater height that for this design means a cross section of the surface with higher bending stiffness. Bending stiffness is the property for which the shape is designed. The folds can be placed with different spacing over a surface and in different directions.

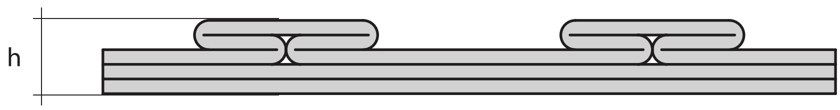


Figure 097. Height of structure at fold.

A textile can be folded in different directions to account for stresses in different directions. The textile is still continuous and therefor this technique is beneficial with regard to bonding lengths, as opposed to previous techniques.

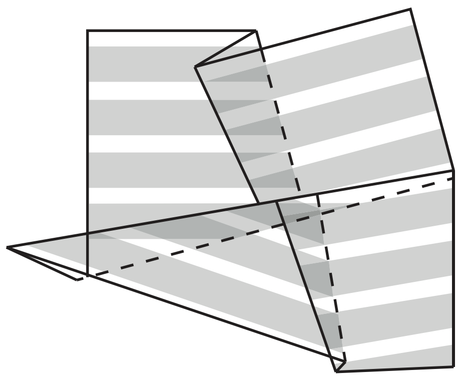


Figure 098. Left: Fold that change fibre direction. Right: Folded twice.

17.1.2 DESIGN POSSIBILITIES

Folding in combination with the manufacturing method of vacuum injection gives a textured surface where the folds are both visual and tactile. The folds get a small shadow from their thickness. There is a contrast in the hard, cast composite and the visually soft appearing folds.

The design was carried out using sparsely woven metal and plastic textiles. The folds gives three layers of textile on top of each other with different directions, which creates new, latticed patterns from the striped layers. The possibility of folding in several directions further increases the possible patterns available.

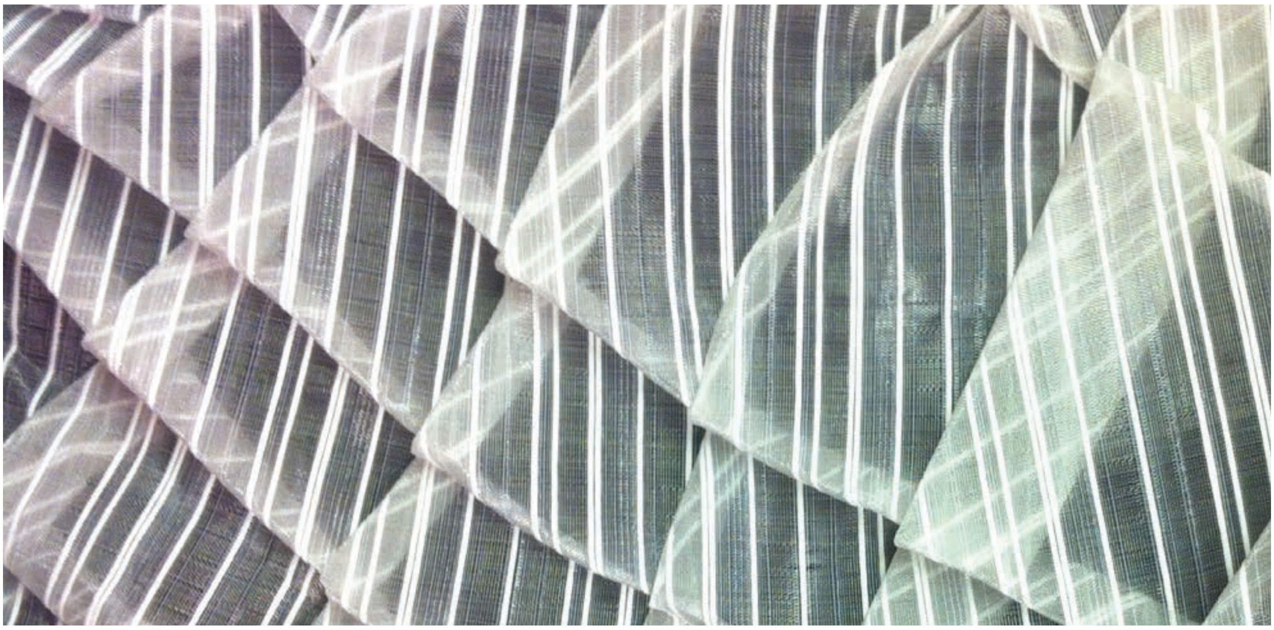


Figure 099. Folds from the sample infusion, before infusion.

17.2 TEXTILE PATTERN, FORM AND ANALYSIS INTEGRATION

17.2.1 COMMUNICATION TOOLS

The stress analysis of the preliminary design was communicated using scale models of CNC (Computer Numerical Control) cut EPS (Extruded Polystyrene) foam and felt tip pens. The principal stress distribution was drawn on the scale model using red for tension and blue for compression, many lines where the stress was large and few where it was small. The lines also indicated the direction of the tensile and compressive forces.

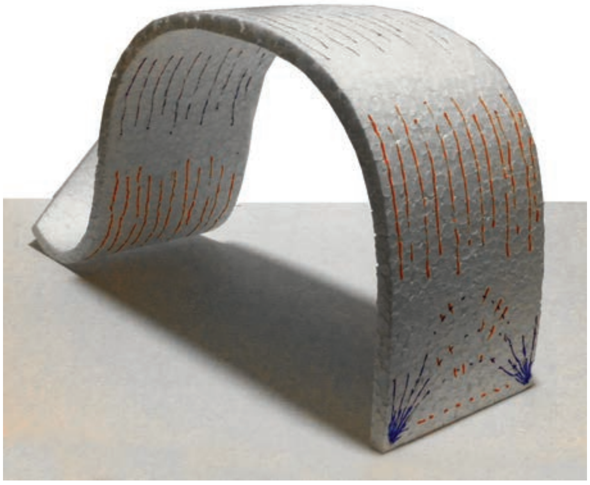


Figure 100. Communication tool.

17.2.2 TRANSLATING THE FORCE PATTERN INTO A FOLD PATTERN

The model was then discussed regarding which type of fold would answer to which type of force. In consultation with Dr Mats Ander we decided to use folds in the direction of the force over areas with large tensile forces and small compression forces. These folds should be long folds over the whole area affected by the tensile stress. When the force shifted to a dominant compressive force we assumed direction would be of less importance, since mainly the epoxy resin would handle compressive forces. Still, the textile is not only reinforcement but also binds epoxy, and it is therefor, indirectly, strengthening to have extra textile also in areas with large compressive forces. In the areas with large compressive forces we allowed for a more free expression in the folds.

The difference in folds between alternately compressive and tensile dominating forces creates a variation that is aesthetically interesting. That the aesthetic expression is derived from the analysis is important in the sense that the structure may become more efficient, but it is important to stress that the final design of the composite should stand on its own, whether or not the force pattern is legible.

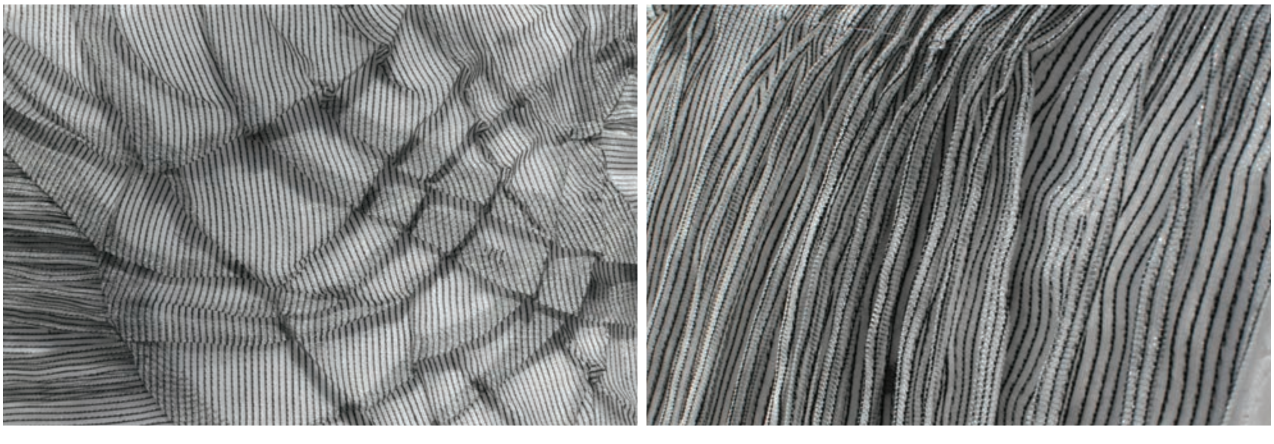


Figure 101. Left: Random folds. Right:

18 SAMPLES IN FOLDING TECHNIQUE

Before creating the last prototype we had now learned to make smaller samples first to learn from. The new technique we were exploring was folding and we tried several material combinations with this technique.

The structural qualities of folding are

1) A local thickening of the laminate due to the fold
2) Continuous fibres, with long anchoring lengths

In earlier samples and prototypes we had trouble with large change in colour due to wetting. To have better control we decided to introduce metallic and synthetic fibres that kept their colour as wet. We continued with core layers of flax, but changed the layer directly under the folded textile. Experiments with white and black synthetic weave, and a light blue coloured flax weave where done. To work with this underlying layer became important since the top layer weaves where sparsely woven.

The textiles manufactured with predominantly metallic threads would stay in shape after folding, without extra threads for fixing. Other textiles were sewn down to stay in position during the infusion procedure. For some textiles the folds was possible to keep in shape by ironing. The orientation of the folds is of great importance to the performance of the composite, and even small deviations have large effects on its properties, as discussed in chapter 5. We experienced that the folds in the metallic textile and the ironed down folds were easier to manufacture and keep precise than the sewn folds.

On the following pages the resulting samples are presented.

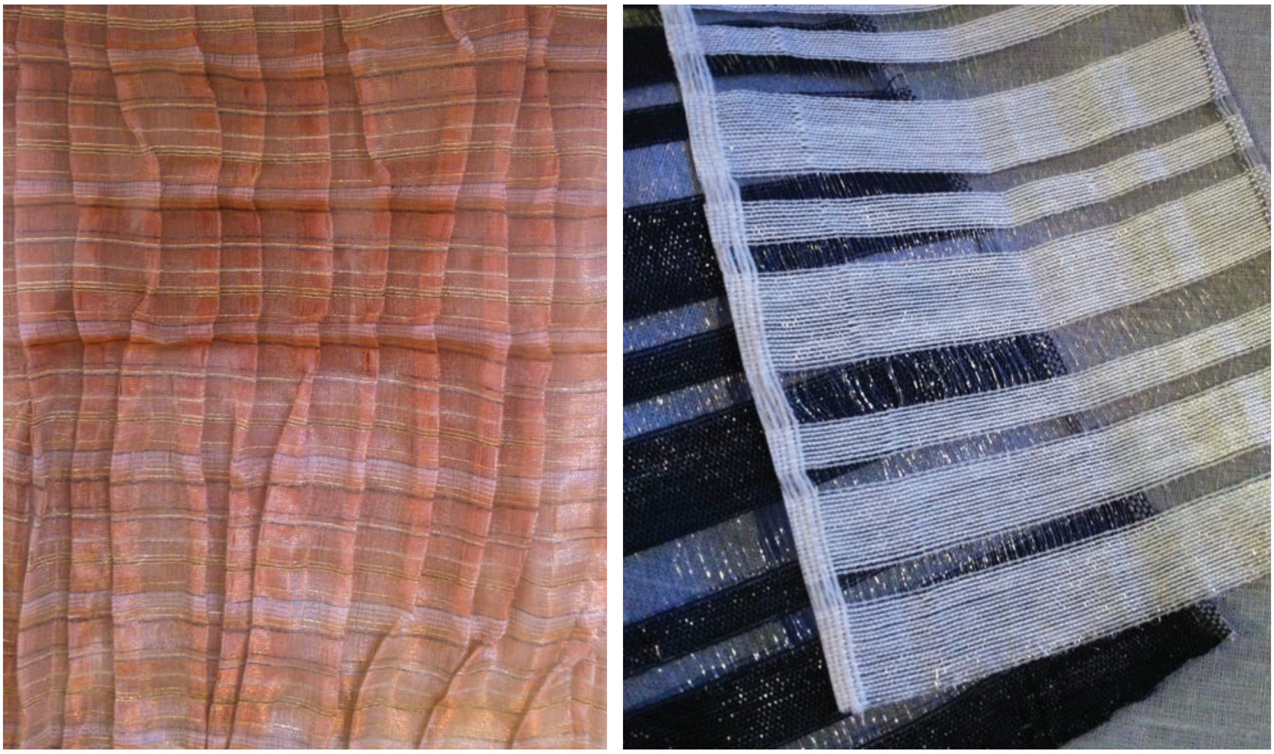


Figure 102. Dry samples. Right: Monofilament warp with weft of metallic threads. Left: Monofilament warp with synthetic and cotton weft.

Figure 103. Samples as displayed at Formex fair 2014. Composite sample in copper-monofilament textile and epoxy. Textile, dry sample, in copper-monofilament weave.

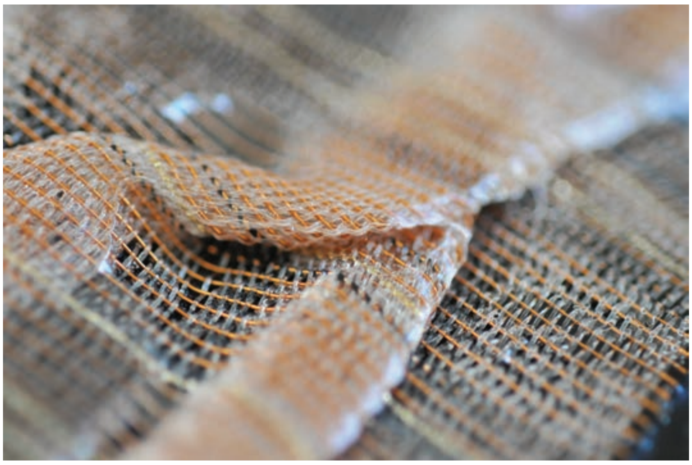
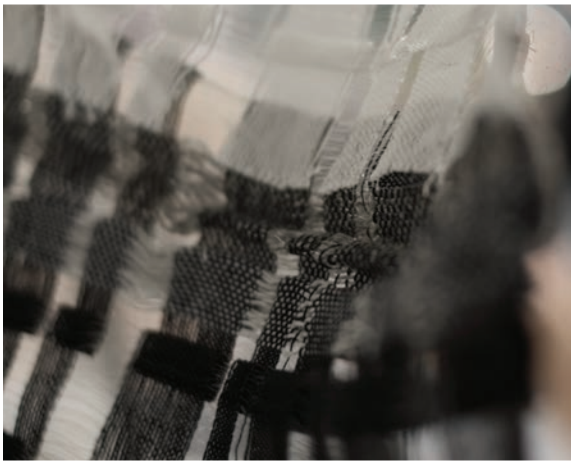



Figure 104. Left: Detail picture of copper-monofilament textile, epoxy matrix. Right: Dry textile sample.

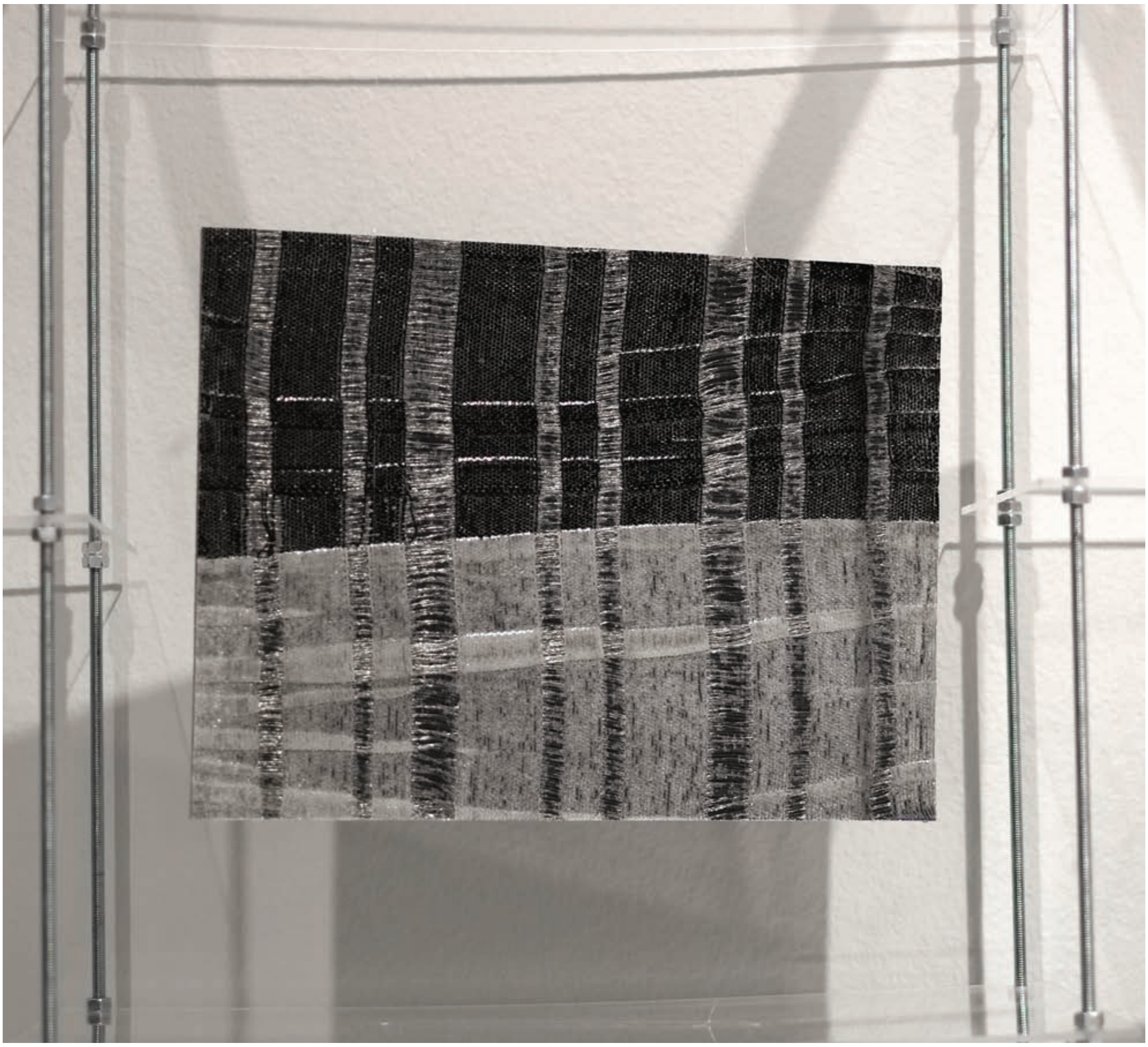


Figure 105. Composite sample as displayed at Formex fair 2014. Folded textile.

Figure 106. Samples as displayed at Formex fair 2014. Composite sample metal-polyester-monofilament textile, epoxy. Textile dry sample.

Figure 107. Detail picture of composite sample, metal-polyester-monofilament textile, epoxy matrix.

Figure 108. Composite sample, copper-monofilament textile and epoxy resin. This sample was infused without core layers.

Figure 109. Composite sample, polyester textile and epoxy resin.

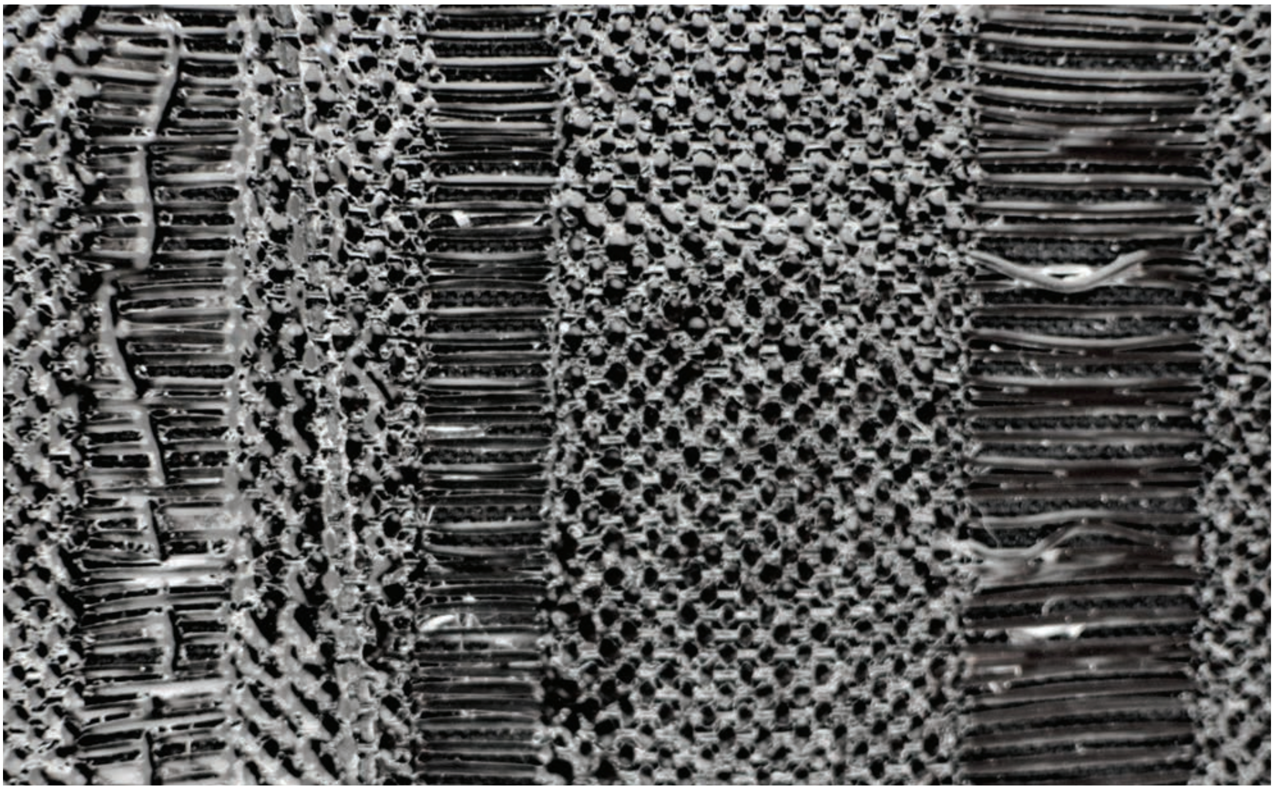


Figure 110. Detail image of composite sample. Polyester textile and epoxy matrix. Flax core layers and polyester textile as second layer.

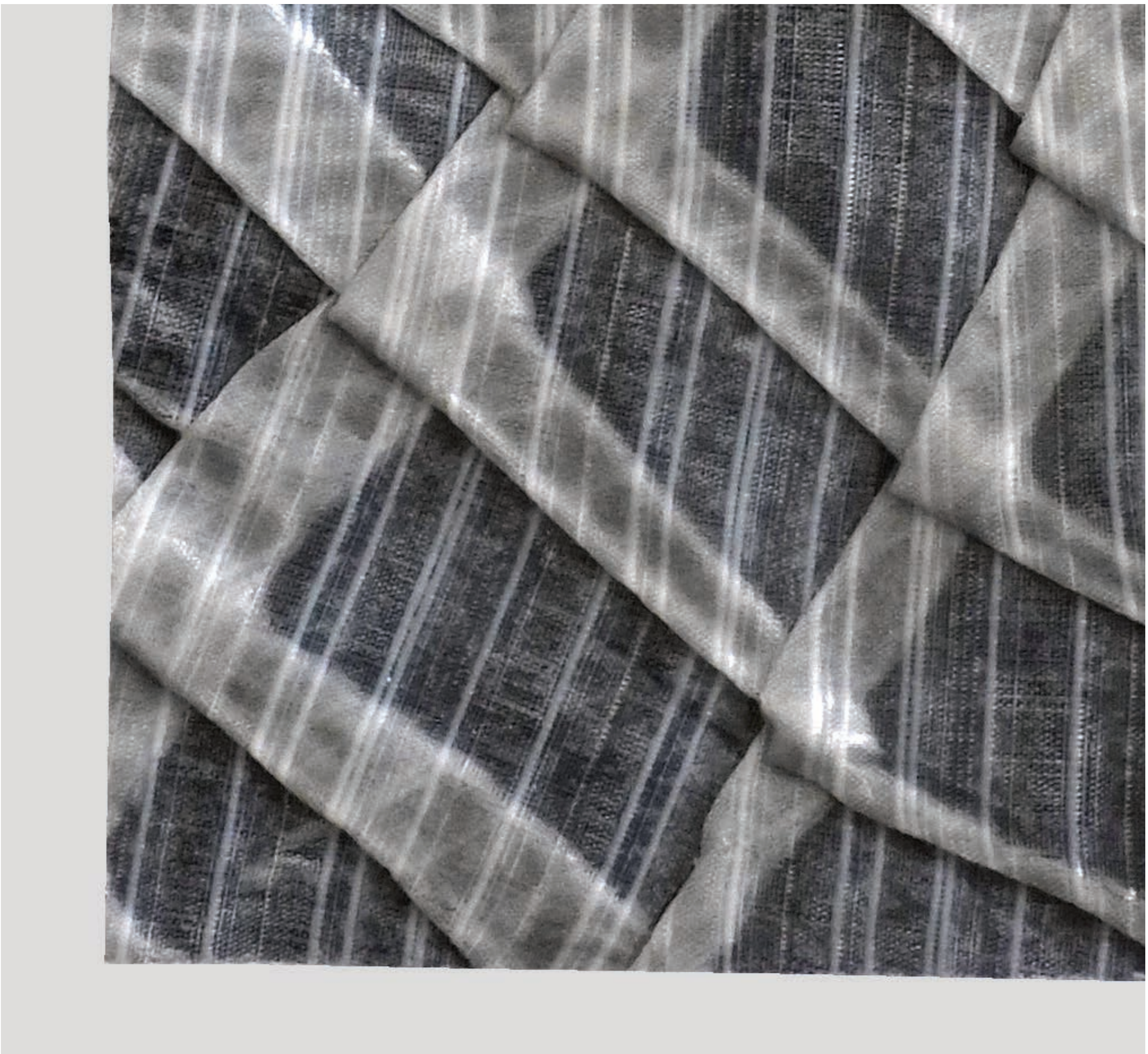


Figure 111 & 112. Detail and full picture of composite sample, metal-polyester-monofilament textile in epoxy matrix.

Figure 113 Detail and full picture of composite sample, metal-polyester-monofilament textile in epoxy matrix.

19 PROTOTYPE THREE

19.1 REFLECTION ON PROTOTYPE ONE AND TWO

The last prototype of the project was made with a folded textile technique. We developed a new form in order to resist the deformations induced by the vacuum bagging process. In the earlier prototype tests the vacuum caused the layers to wrinkle over concave forms. With fewer layers the problem appeared to increase. Due to the geometry of the form and lack of friction at the supports, the prototype became somewhat unstable when placed on smooth surfaces. This was also a reason for increasing the amount of layers and volume of resin used.

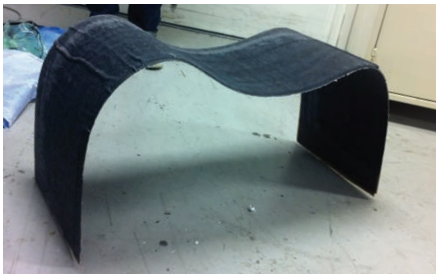
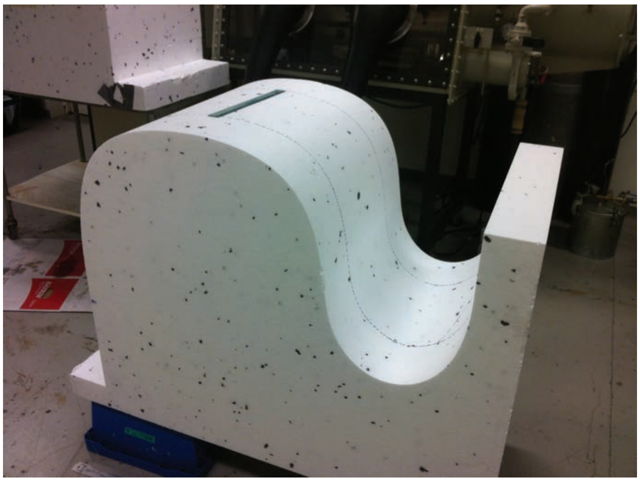


Figure 114. Left: Prototype one. Right: Prototype two.

19.2 TOOL AND SET-UP

The tool for this final prototype was manufactured with extra space for tubing and tape, as well as a "drip shelf" (figure 115). To make the prototype sturdier and to avoid wrinkling, prototype three was manufactured with 15 core layers of flax in a symmetric lay-up of plain and +45/-45 weaves. The core layers were alternated with distribution weaves (blue weaves in figure 115). Release weaves were used to get a matte surfaces. The layers were kept from sliding by tape at the ends (figure 116).



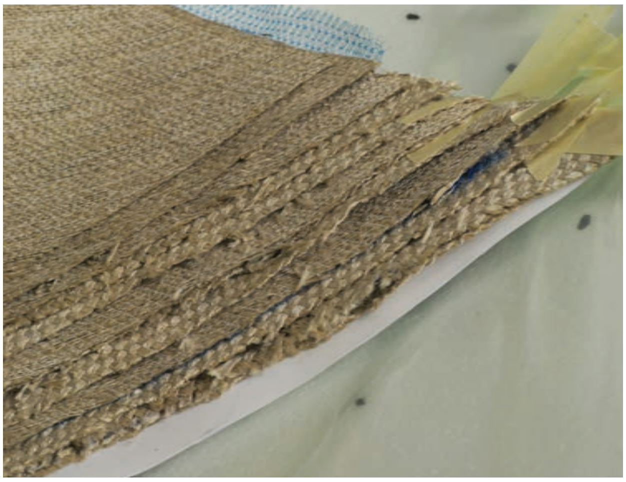


Figure 115. Left: EPS tool with guidelines for placing the textile layers. The tool is manufactured with extra spaces for the sealing of the bag and tubing. Right: Close-up of flax core layers.

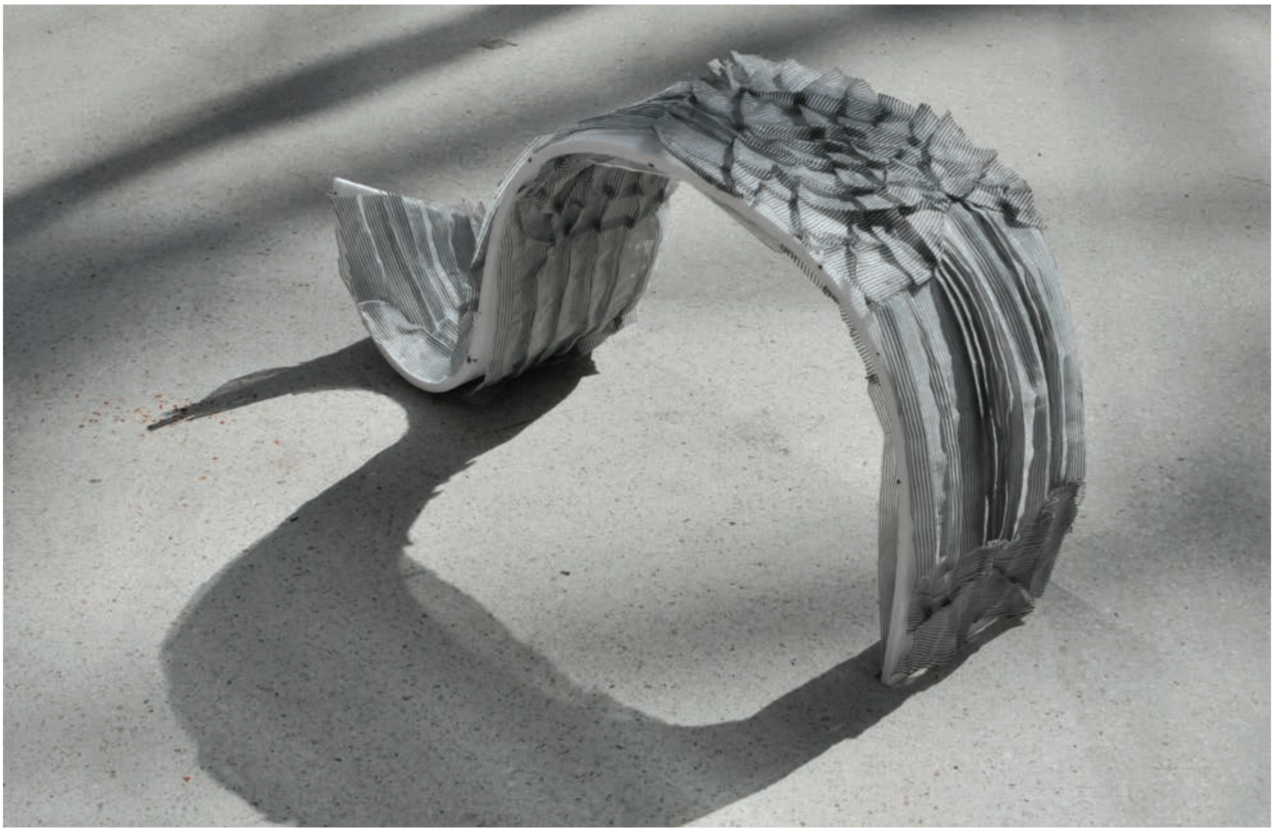


Figure 116. Dry chair.

The dry textile was folded and pinned onto a hot wire cut 1:1-model, with the small communication model as model.

19.3 MANUFACTURING

Prototype 3 vacuum injection at Sicomp. The cut off metal threads in the fabric punched small holes in the bag that created air inlets. The holes are covered here with tacky tape, but the holes on the underside were not reachable which made the laminate weaker.

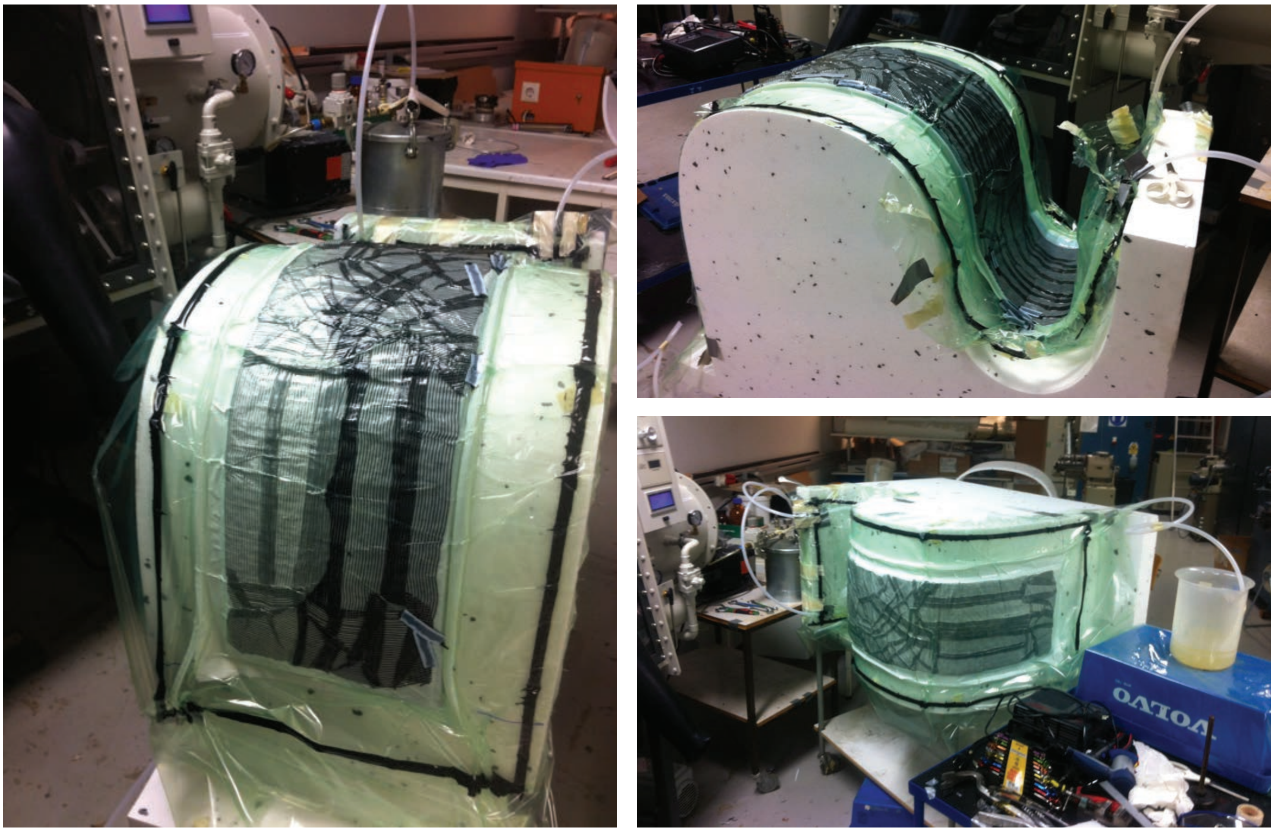


Figure 117. Manufacturing process.

The injection is done over the shortest distance. This is due to the hardening of the resin, if the injection takes too long it will start to cure and block new resin from filling the remaining parts. It is also to get a more even laminate, since the pressure is 1 atmosphere at the inlet and around 100 bars at the pump there is a risk for thickening of the laminate at the inlet side as the resin cures. To always inject over the shortest distance minimizes this effect. For this injection we tried flipping the tool to increase the pressure and fasten the process, but it did not help since the vacuum clamping the layers and bagging to the tool was not enough to hold it and it started to fall off. Instead we placed the epoxy container high for more pressure and used extra large pipes to increase speed. Learning from earlier mistakes, the epoxy was mixed 2-4dl at the time as to prolong pot life. When the epoxy cure it is an exothermal process, and heat speeds up the curing process for the remaining resin.

As can be seen in figure 117 we had problems with wrinkling. In the concave shape of the tool we have large deviations from the tool. In the convex or seating-part of the tool wrinkles occur too. Even though there are more layers than needed the force created from the vacuum pump still wrinkles the material. Through applying the vacuum step by step the wrinkles can be somewhat smoothened and relocated a few centimeters back and forth to place them where the folds of the pattern are more random and the wrinkles are slightly less visible.

19.4 RESULT

The resulting chair was a failed prototype in some ways. Since we designed the chair with 15 core layers of flax its aesthetic expression was compromised even though the chair became very stiff and heavy. The number of core layers also lessened the impact of the folded layer, making it a solely aesthetic layer. This was not the integration of textile and structural design we aimed for. There were problems with wrinkles, affecting both the desired appearance and quality of the prototype.

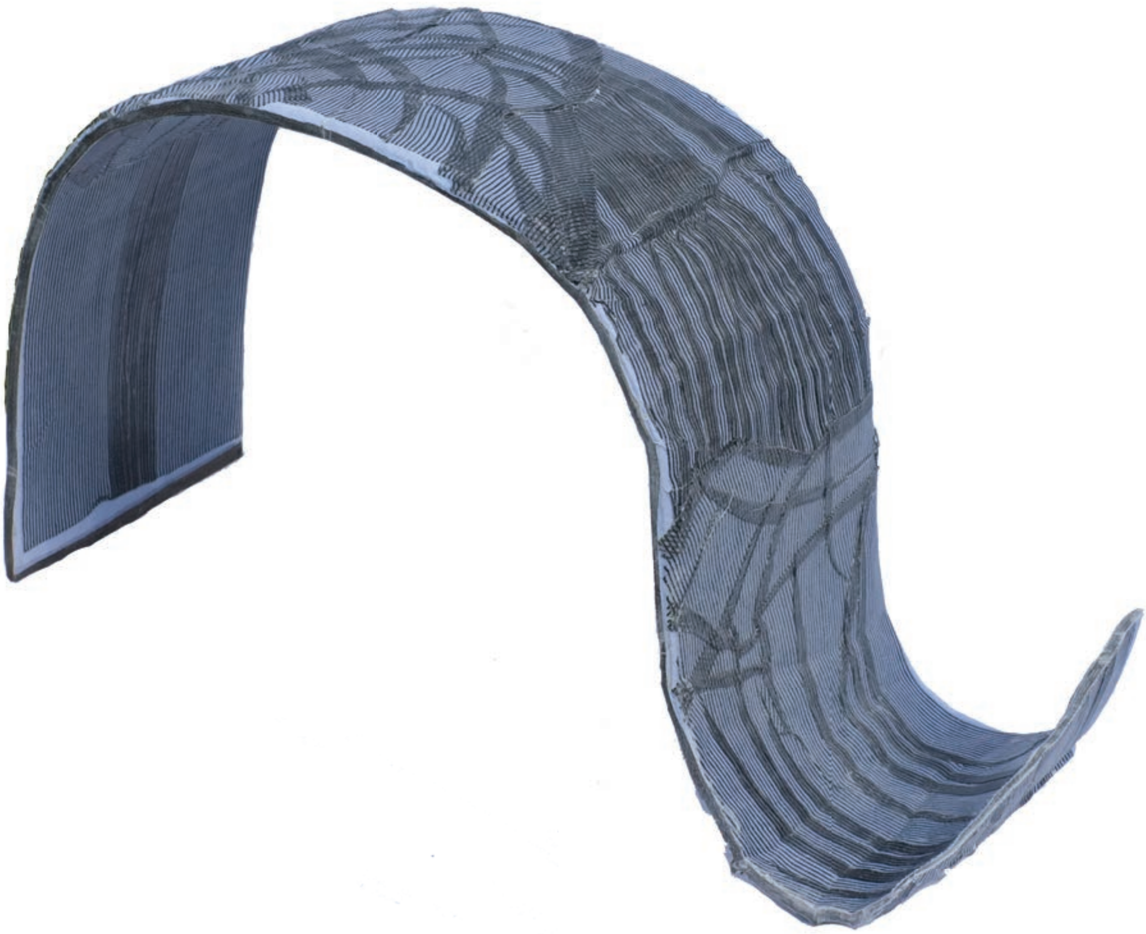


Figure 118.Chair. Now exhibited at Smart Textiles Showroom, Swedish School of Textiles.

20 STRUCTURAL TESTING

20.1 3-POINT BENDING TEST

To validate our assumption that folds can increase bending stiffness we conducted a three point bending test and a density test in order to calculate the ratio between stiffness and density for folded and non-folded samples.

We manufactured sample tests in carbon fibre and epoxy of three different types (figure 119). Sample A is a reference sample with a regular, non-folded stack-up. Sample B and C are versions of the folded sample, with the same amount of fabric as sample A. In sample B the textile is folded and in C the folded layers are cut with the same general geometry as B.

The infusion is done across the shortest distance to avoid possible thickening effects due to pressure difference over the length of the sample. Three samples of each type are manufactured.

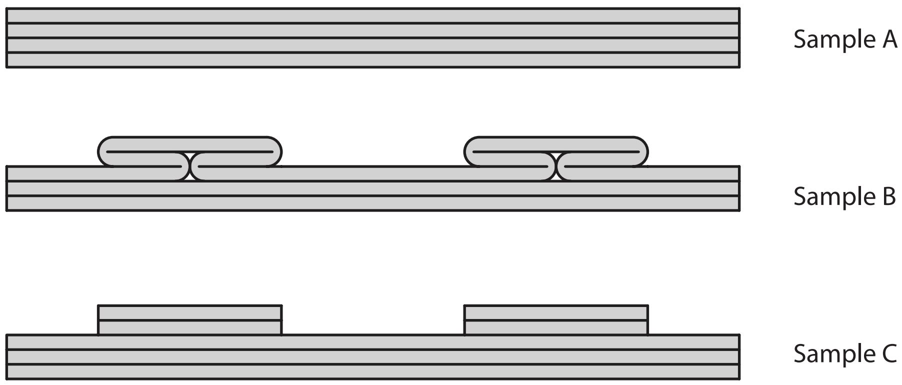


Figure 119. Illustrated section through the samples.

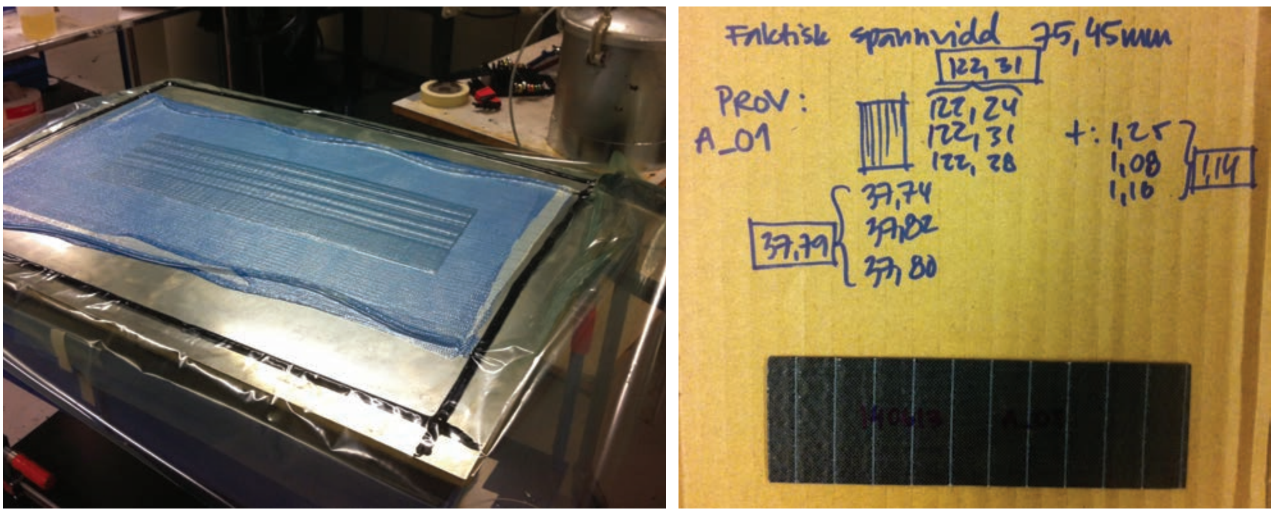


Figure 120. Left: Manufacturing the samples for the bending test. Right: The first sample cut out and measurements for the sample and testing set up are noted.

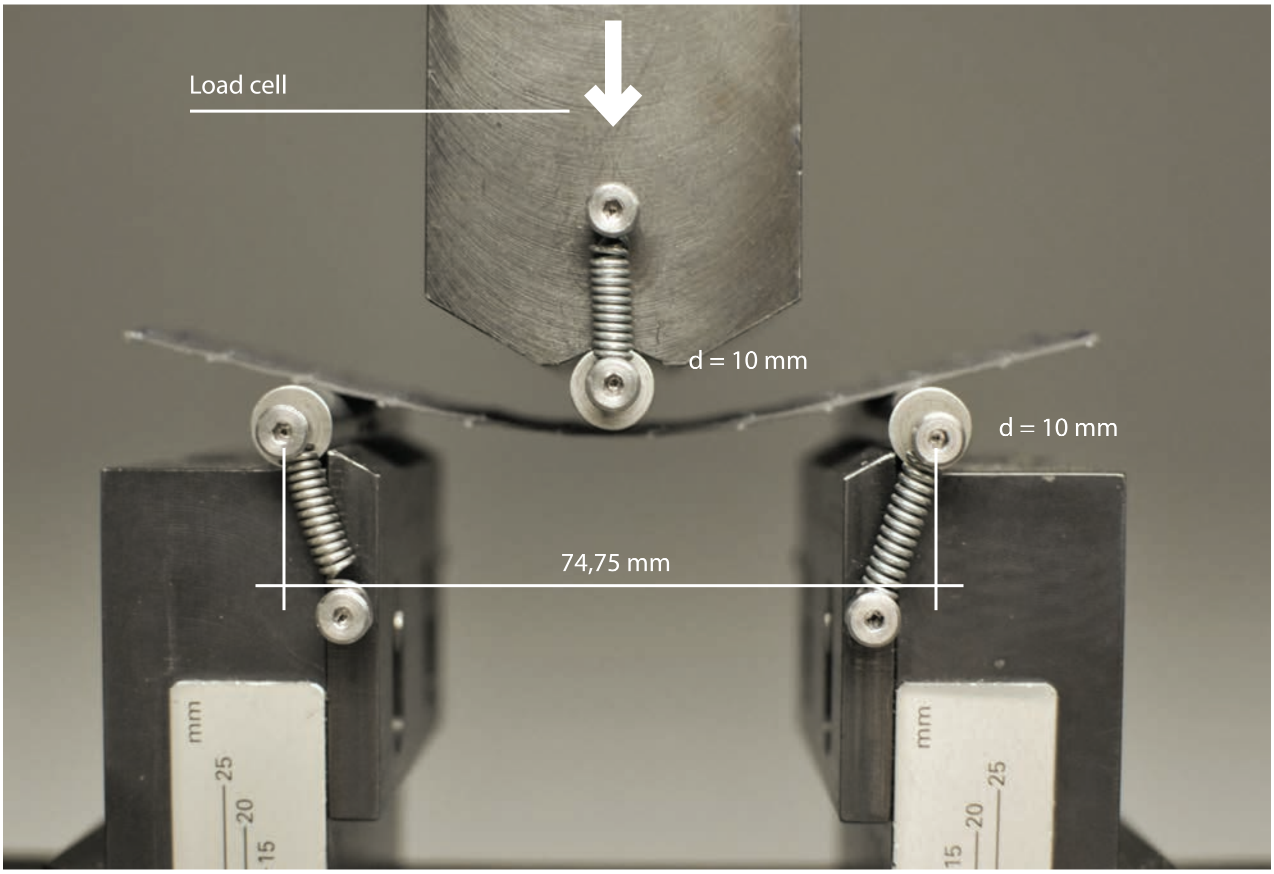


Figure 121. Experimental set-up for the 3-point bending test and a tested sample. Sicomp laboratory.

The 3-point bending test was done according to Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials as issued by ASTM International (Designation: D 7264/D 7264M - 07). The test samples deviated from the method as they had a ratio between length and thickness of 1:47, higher than the suggested ratio of 1:30. The test measured deflection and added a load of 1N every second.

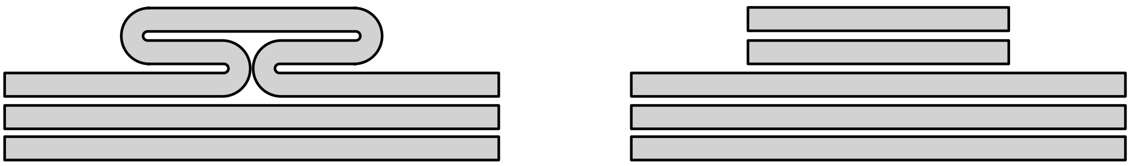


Figure 122. Left: Illustrated cross section through a folded stack-up. Right: Illustrated section showing how the stack-up was modeled for the FE-analysis. Fibre direction perpendicular to cut.

From the elementary case of a simply supported beam, as the 3-point bending test represent, the bending stiffness of the samples were determined and compared.

$$\delta = \frac{PL^3}{48EI} \quad \rightarrow \quad EI = \frac{PL^3}{48\delta}$$

Data from the 3-point bending test:

$$L = 75.45mm$$

$$\delta = 4.0mm$$

$$P_{sample\ A,mean} = 105.4N$$

$$P_{sample\ B,mean} = 141.8N$$

$$P_{sample\ C,mean} = 143.9N$$

Bending stiffness calculation and comparison:

$$EI_{sample\ A,mean} = 0.2385Nm^2$$

$$EI_{sample\ B,mean} = 0.3209Nm^2$$

$$EI_{sample\ C,mean} = 0.3256Nm^2$$

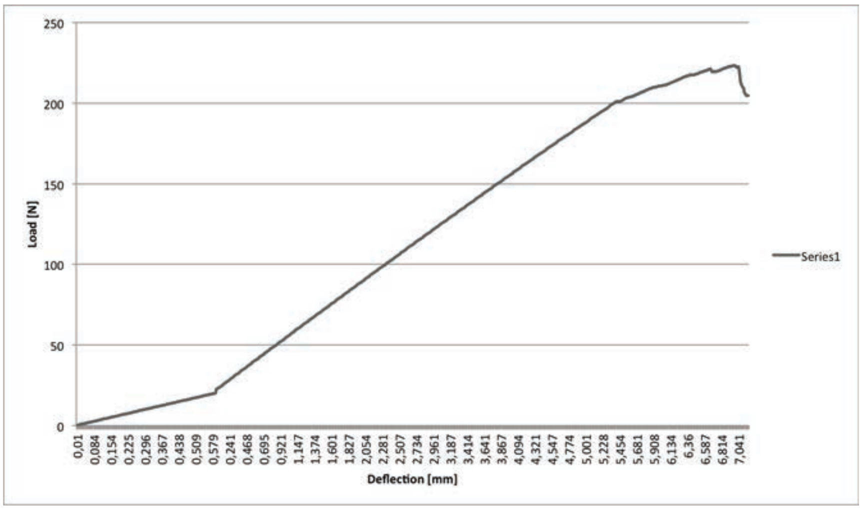
$$EI_{sample\ B\&C,mean} = 0.3233Nm^2$$

$$\frac{EI_{sample\ A,mean}}{EI_{sample\ B\&C,mean}} \approx 0.7378$$

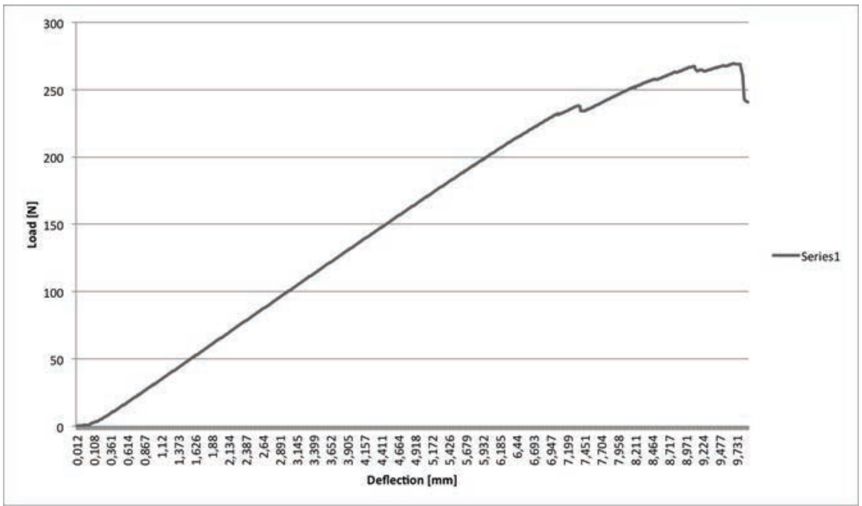
$$\frac{EI_{sample\ C,mean}}{EI_{sample\ B,mean}} \approx 0.9854$$

The test indicated that the samples B and C, that had folds and cut folds respectively, have a bending stiffness that differs only 1,5%. This is within the variation of equal samples. This result indicate that a folded composite may be modeled as a cut one of the same overall geometry, which has relevance for FE-analysis models.

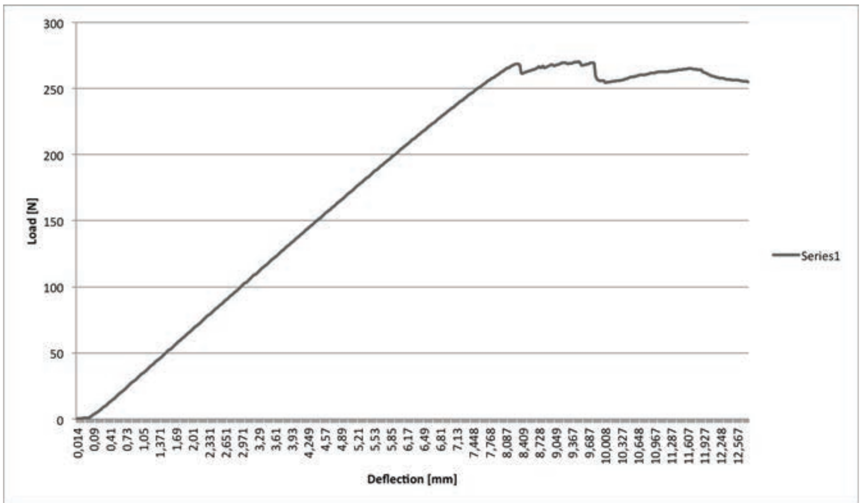
The mean value for the bending stiffness of samples B and C are 26% higher than the bending stiffness measured for sample A. This indicates that the folds improves the static structural behavior with regard to bending stiffness. But it is possible that the folds have created pockets where epoxy is lodged. To make up for this possible defect the density of the pieces are measured.



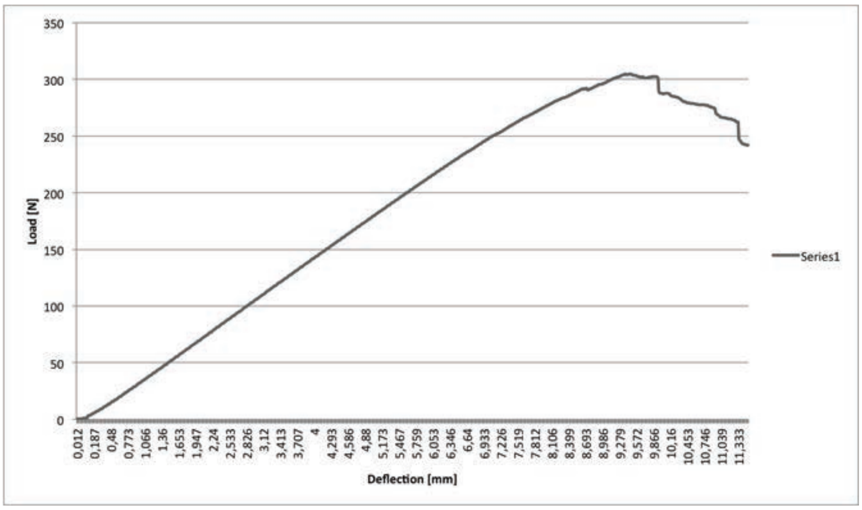
Sample B01



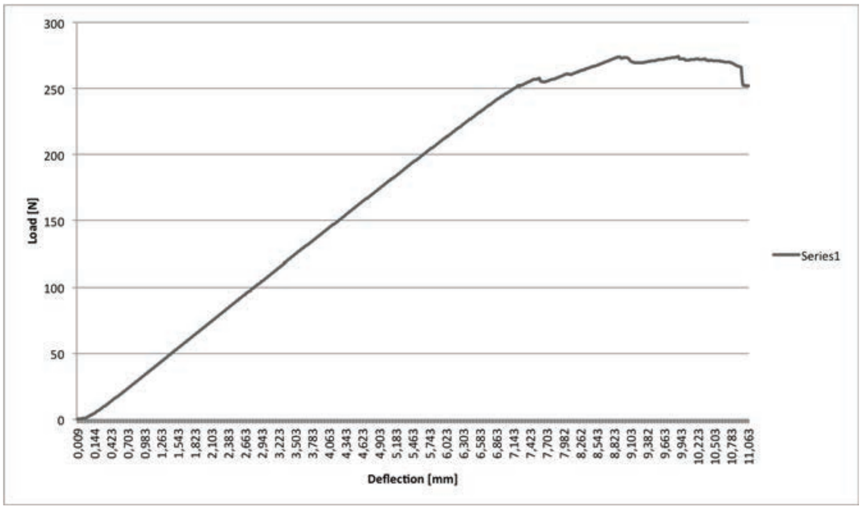
Sample B02



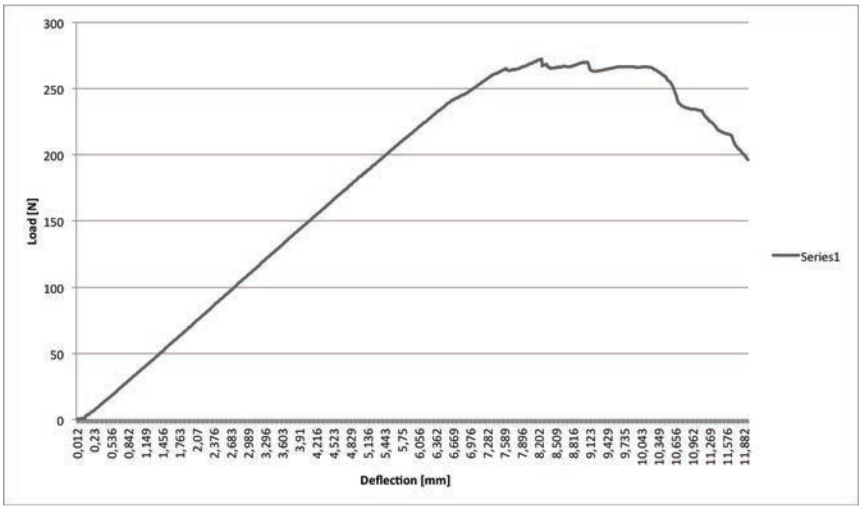
Sample B03.
Figure 123. Results of the 3-point-bending test.



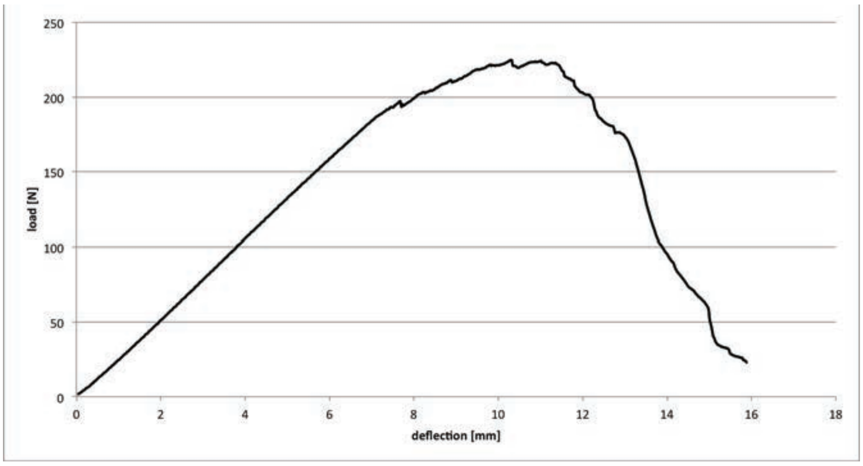
Sample C01



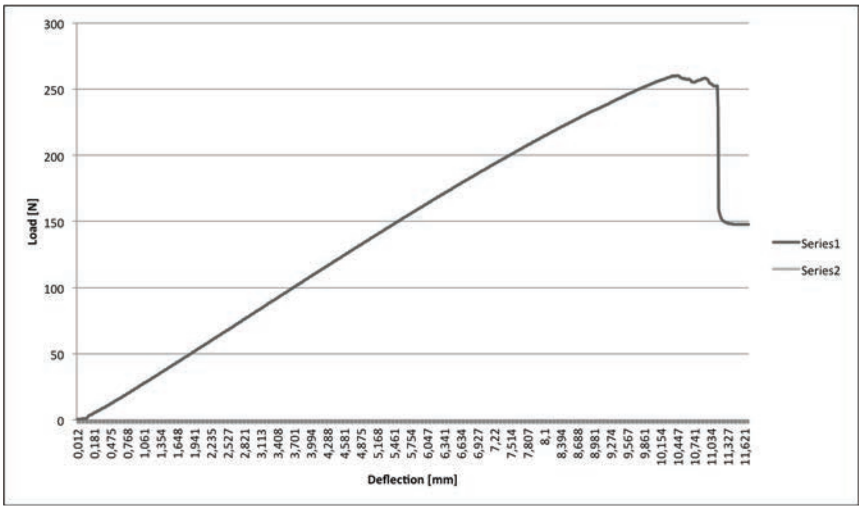
Sample C02



Sample C03.
Figure 124. Results of the 3-point-bending test.



Sample A01



Sample A02

Figure 125. Results of the 3-point-bending test.

20.2 DENSITY MEASUREMENT

The density of the samples was measured with a hydrostatic weighting method, based on Archimedes's principle. The density is calculated according to the following equation:

$$\rho_{sample} = \frac{weight, dry}{weight, dry - weight, soaked} \times \rho_{water,13°C}$$

The scale used was a electromagnetic scale with 0,01 grams accuracy. Figures below show the experimental set-up.

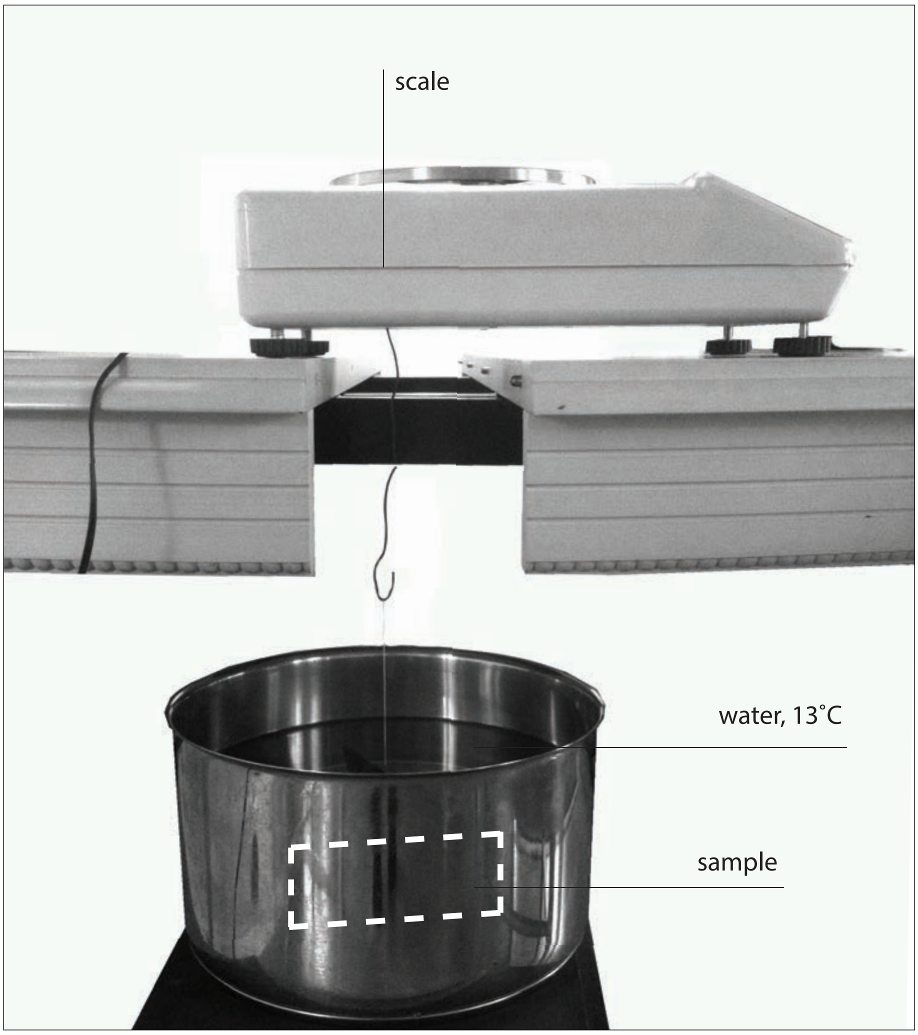


Figure 127. Set-up for the density measurement.

Sample	*Weight, dry*	*Weight, soaked*	*Density*
Sample A_01	6,18g	1,74g	1,39 g/cm^3
Sample A_02	6,58g	1,76g	1,43 g/cm^3
Sample B_01	7,67g	2,30g	1,42 g/cm^3
Sample B_02	7,37g	2,31g	1,46 g/cm^3
Sample B_03	7,35g	2,26g	1,44 g/cm^3
Sample C_01	7,54g	2,19g	1,41 g/cm^3
Sample C_02	7,16g	2,20g	1,44 g/cm^3
Sample C_03	7,30g	2,22g	1,44 g/cm^3

Density of water at 13˚C is 0,999377 g/cm^3.

Average values for the sample densities are

Sample A	1,41 g/cm^3
Sample B	1,44 g/cm^3
Sample C	1,43 g/cm^3

The difference between the samples are within the error margin of 0,05 g/cm^3.

The result of the density measurement is that all samples have (within the error margin of 0,05g/cm^3) the same density. This implies that the fibre to resin ratio is the same for all samples, and the bending tests are therefor comparable.

It is also possible to compare weight to stiffness, to make up for differences induced by cutting the samples. The dry weight of samples B and C are 1,5g higher than sample A, or they are 20% heavier. This is due to differences in the cut width of the samples, sample A are not as wide. However, the most important factor for the bending stiffness is the height of the sample.

20.3 SIMPLIFIED FE - MODEL

As described above the 3-point bending test indicated that a cut sample behaves very similar to a folded sample. The geometry for the FE-analysis could thus be modeled as the cut sample (figure 122 right), which is faster to model as a geometry and more straightforward to mesh. The meshing method for this analysis was quadrilateral elements. Three individual stack-ups was defined for each part of the model. The connection between the “folds” and the body of the sample was defined as “attached” (Ansys 14.5 User’s Guide).

The sample modeled employs the ACP Pre/Post composite component in Ansys and models the unidirectional carbon fibre-epoxy stack-up.

The material data for the FE-analysis was based on the elastic modulus extracted from the reference sample, sample A. The result between the FE-analysis and the physical test differ. The deflection is only 2,2mm, for a load of 142N, for the FE-result and the 3-point bending test gave a deflection of 4mm for the same load. Possible error sources are the insuffcent data for the material properties and that the connection between layers and the “folds” are modeled too rigid.

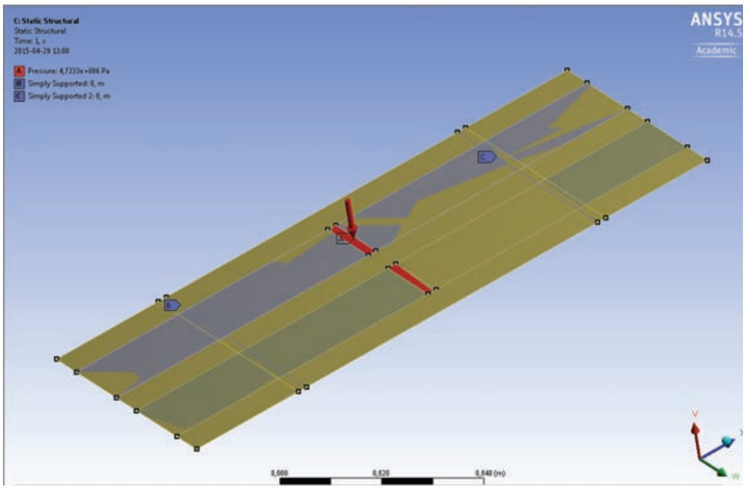


Figure 128. FE-analysis set-up in Ansys Pre/Post composite component.

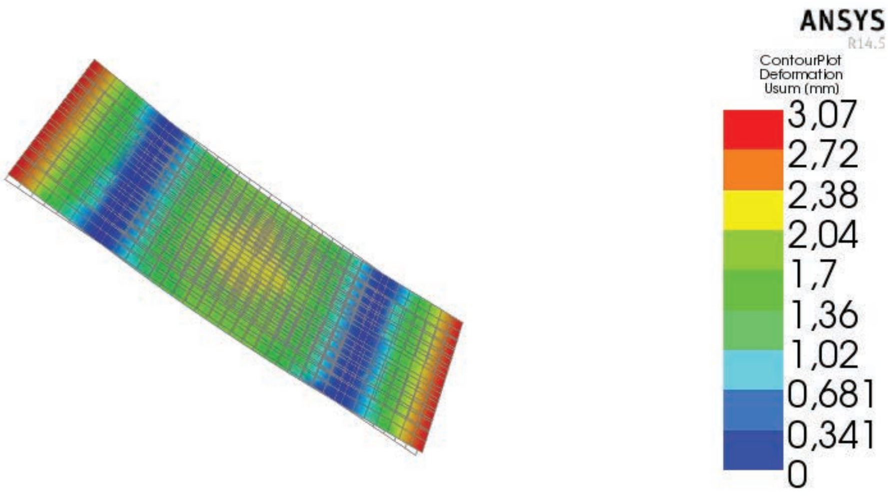


Figure 129. Deformation of sample.

21 SOCIAL AND ENVIRONMENTAL SUSTAINABILITY

This thesis regards development of a structural material. Here it is applied to a furniture scale, but can also have applications in the building industry. The construction of buildings has a large effect on our carbon footprint. As much as 16% of our carbon footprint in Sweden is due to the construction industry (Bygg- och fastighetssektorns miljöpåverkan, 2010). Looking at a British study of their building related carbon emissions 90% of these emissions are from structural clay based products (Estimating the amount of CO_2 the building industry can influence, 2009). Concrete and steel have a large impact on the environment. Alternative materials compatible with a sustainable development are needed.

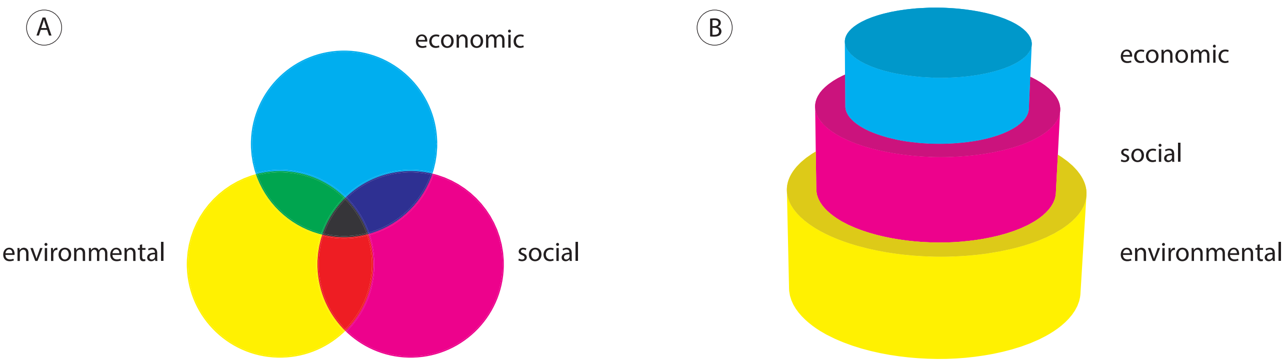


Figure 130. A The Venn diagram of economic, social and environmental sustainability, B Hierarchic scheme of sustainability.

Sustainable development is a socially constructed term that has become meaningless through its many definitions. A common way of describing it is with a Venn diagram, figure XX. This suggests that ecological, social and economic sustainability are intertwined and equally important. Another way to view sustainable development is to see these segments in a hierarchy, dependent on each other (figure XX). This presents the idea that the base for any development is an ecologically sustainable development. Then social and last economic needs can be met (Hållbarhetens Villkor, 2012).

This chapter is therefor focused on ecological and social sustainability.

21.1 ENVIRONMENTAL SUSTAINABILITY

The composite materials manufactured in the scope of this thesis work have several properties that benefit the environment.

1. All materials of the composite samples can be exchanged for renewable alternatives with small CO2 emissions, something that is not possible in for example concrete.
2. Composites are lightweight materials that can reduce emissions through lighter structures and transports.

3. Composite materials can, to different extents depending on its constituent materials and other conditions, be recycled.
4. Man-made materials such as composites produced in a controlled environment have smaller deviations and demand smaller safety margins in dimensioning.
5. Composite materials can be designed and manufactured for each application, further reducing weight and increasing material optimization possibilities.

In this thesis work we have worked with epoxy as resin and several natural fibres plus metallic fibres as reinforcement. Epoxy is a non-renewable, oil-based product with carbon emissions. Bio composites use starch-based resins made from corn or other plants. For our project we choose to work with epoxy since it was easily available to us through Sicomp. The knowledge and experience of epoxy at Sicomp was something we benefited from. A natural continuation of this work would be to work with biobased resins.

Wool fibres are a renewable resource locally produced in Sweden. The wool used for this project is of a coarse quality that is usually burnt or dug into the ground. Since the fibre is cast into resin the coarseness is no problem. There are other problems with wool as a structural material that has been covered in earlier chapters. Flax fibres are also local to Sweden and a renewable resource. Metallic fibres can be recycled.

Composite materials can create lightweight solutions. H Damberg et al writes: "Since weight and energy reductions together with a prolonged life span can be obtained for composite materials, this implies a reduction in the use of raw materials, which can be of great environmental benefit." (translated from Swedish, Komposithandboken, 2001). Lightweight materials also have benefits

Figure 131. Shredded carbon fibre scrap waiting to be recycled.

Waste of composite materials can be handled through reuse, recycling, landfill or incineration. Recycling refers here to either mechanical recycling or chemical recycling. In mechanical recycling the composite material is milled down and are down cycled to filler in new composites. In chemical recycling the plastic is degraded, giving high quality raw materials without loss of properties. Fibres can be recycled, but not with preserved properties. (Komposithandboken, 2001)

The challenge for recycling of composite materials is a high investment cost but above all to get a continuous stream of material. Mechanical recycling has lower investment costs but does not recover raw material.

Many of the processes for composite materials generate a lot of production waste. The amount of waste and scrap typically ranges between 5 and 10%. These materials are generally not contaminated and are also well collected, with known characteristics, which provide good opportunities for profitable recycling.

The attitude towards recycling opportunities can be drawn from the following statement: ”In today’s political climate, each manufacturer is willing to use recycled materials whenever possible provided that the product quality is maintained and any increase in costs is offset by the marketing benefits.” (P-A. Löfgren, M. Wennerbäck, red. H. Damberg, 2001). This reflects the views represented by the Venn diagram in figure 130 rather than the hierarchal scheme. Perhaps the demand for sustainability and recycling needs to come from a higher instance for it to really affect the industry.

21.2 SOCIAL SUSTAINABILITY

Social sustainability can be defined as “*There are several approaches to social sustainability. The first, which posits a triad of environmental sustainability, economic sustainability, and social sustainability. It is the most widely accepted as a model for addressing sustainability. The concept of “social sustainability” in this approach encompasses such topics as: social equity, livability, health equity, community development, social capital, social support, human rights, labor rights, placemaking, social responsibility, social justice, cultural competence, community resilience, and human adaptation.*” (Wikipedia, 2015). We focus here on cultural competence and community resilience.

In this thesis work we aim to integrate structural design and aesthetic expression. Our belief is that this could help increase the understanding of structures, and maybe increase the interest for composite constructions and design.

The unique expression of a tailored composite structure can be used to create identity and add value to a building or piece. This can lead to longer lifespan of the structure and a better place for people to be. Making the textile be a part of both the construction and expression develops the textile in furniture from a surface material to a structural reinforcement. To the techniques applied in this thesis work is a measure of handcrafting. In folds, in braiding, in weaving and in cutting different handcrafting techniques are used. To use handcrafting together with modern materials and production techniques helps to sustain or sometimes revive the value and knowledge of our cultural heritage.

21.3 SUSTAINABLE MATERIALS IN CHALMERS EDUCATION

Many new solutions and materials are already available to the building industry. But this needs to be combined with a modern education at our universities to be implemented. A student should be able to compare the impact of different material solutions to a construction problem and have knowledge of sustainable construction materials and typologies.

Traditional materials are not always suited for our current condition. A standard material like concrete is today sustainably controversial.

22 RESULT

The thesis work *Within the Same Thread* has resulted in a composite material manufactured with the textile technique of folding. The designed composite has a higher bending stiffness per mass unit ratio than an unfolded, regular composite. The composite has a designed aesthetic expression, both visual and tactile, employing the folds.

In bending a folded composite sample is around 26% more efficient per mass ratio than that of an unfolded composite of the same construction. The increase of stiffness is due to the change in distribution of the fibres. The composite bending stiffness was calculated from a 3-point bending test done at Sicomp research laboratory. The test also verified that a folded composite can be modeled for FE-analysis in a simplified way.

Experimental composite manufacturing shows us that a key feature for appearance is absorption rate. An absorbent material darkens and can become more saturated due to wetting, while a material with low absorption rate looks the same or slightly saturated. The most successful samples were accomplished with metallic and polyester fibres, as these could be manufactured with control over the outcome and with clear visual contrast between the constituent materials.

The way of communicating the result of the FE-analysis into a textile pattern, the communication between the engineer and the textile designer, that proved most clear and useful was drawing the force pattern onto a scaled modeled of the prototype.

A side result to our test where that the coarse wool (lovikagarn) proved to be an excellent distributer of epoxy during the infusion process, which may be useful to other purposes than ours. The jacquard patterns we worked with did not have a logical use in the way we employed the technique, but could be further developed.

Figure 132. Sample of folding technique.

23 DISCUSSION

Within the Same Thread aims to investigate design possibilities that can influence the properties of a composite material, both aesthetically and structurally. The aesthetic expression and the static structural behavior are equally important. A special focus lies on the integration of engineering and textile design, aiming for a result where these disciplines act within the very same thread.

To reach our aim we have investigated several textile techniques and material combinations, together with different manufacturing techniques. The result propose a folding textile technique that integrate the aesthetic expression with the structural function. The manufactured samples have shown an increase of stiffness induced by the folding technique. The appearance of the samples made with folding technique are both visually interesting, as they appear both soft and hard, and gives a tactile experience of a hard textile. Thus the aesthetic and structural properties of the composite material resides within the same thread, or perhaps we should say within the same fold.

An important result derived from prototyping was the experience of how different materials and colours were affected by the epoxy wetting process. Our final result, the folded textile composite, make use of monofilament and metallic fibres. Adhesion problems may occur when using metallic fibres and this needs to be further investigated.

The full-scale prototype with this technique did not meet the promise of the sample. The prototype was unappealing due to poor tools and too many core layers. If further developed these problems can be avoided through using an industrial production process. With larger resources the quality of the tool can be improved, for example by milling it in aluminum. The excess amount of core layers was a design problem.

A promising area for folding techniques are applications that require draping around a complex form. Draping fabrics usually causes unwanted folds, but with a folding technique these can be distributed to benefit the design.

The hypothesis for this thesis work was that:

Textile design and materials engineering can through an iterative design and analysis process, using physical prototypes, create an innovative way of working with form and forces in a fibre composite material.

The field of fibre reinforced composite employing the fibre as both aesthetic design and structural design are relatively unexplored. In most composite applications the material is coated. In reference to Eames' fiberglass armchair presented in chapter 5, were the fiberglass is used as an aesthetic finish, the folded textile composite presented here goes further in developing the possible surface texture of the material. Then it comes closer to Wanders' *Knotted Chair* (chapter 5) where the tactility and appearance of textile is very present, through the tactile qualities of the folds. It also shares another important quality with the *Knotted Chair*, that is the handcraft knowledge embedded in these two structures. This knowledge is interesting to preserve for two main reasons: that it can improve new composite structures in the future, and that it is a part of a socially sustainable society to value and develop its cultural heritage.

24 CONCLUSION

Within the Same Thread proposes a folding textile technique for integration of textile and structural design in fibre composite materials. The technique holds promise to have a positive effect on the structural properties as well as providing interesting aesthetic possibilities. A limitation of folding textile technique, as applied in this thesis project, is that the folds have more effect on a few layer, thin composite and little effect on thicker laminates. The handcrafting of the textile demands a labor intensive process, while it also revives the knowledge and creates opportunities for shaping beautiful composites.

Folded textile composites can be modeled for FE-simulation in a simple way. However, the FE-modeling technique needs to be further evaluated for complex geometries.

Further investigations needs to be conducted to verify folding as a feasible and effective method for textiles in fibre composites. Issues such as adhesion between fibres and matrix, ways of draping and possibilities with folds on more than the top layers are all interesting to investigate. As well as more structural testing of different material combinations and fold types.

A low-tech communication process provided a simple and fast way of communicating while leaving room for artistic freedom. In future applications possibilities with an integrated CAD-FE-CAM approach would be interesting to investigate.

25 EXHIBITIONS AND SCHOLARSHIPS

The project has been exhibited at Swedish School of Textiles graduation exhibition EXIT14 and at Formex fair for interior design in Stockholm, division of Young Designers. The samples now have a permanent position at Smart Textiles showroom in Borås. In April samples will be exhibited at Elmia Polymer 2015 in Jönköping. The results are also on display at *www.foldedlogic.se*.

Figure 133. EXIT 14 exhibition in Borås.

Figure 134. FORMEX Young Designers, exhibition in Stockholm.

This project was made possible through scholarships and collaborations. All manufacturing and testing was done at Sicomp in Mölndal, who offered equipment, materials and expertise Smart Textiles has funded the project and are exhibiting the result. Scholarships has come from ARQ, the Swedish architectural research foundation, Britt-Lisa Landahls stipendiefond and TEKO, Swedish textile and clothing industries association are greatly appreciated and acknowledged.

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