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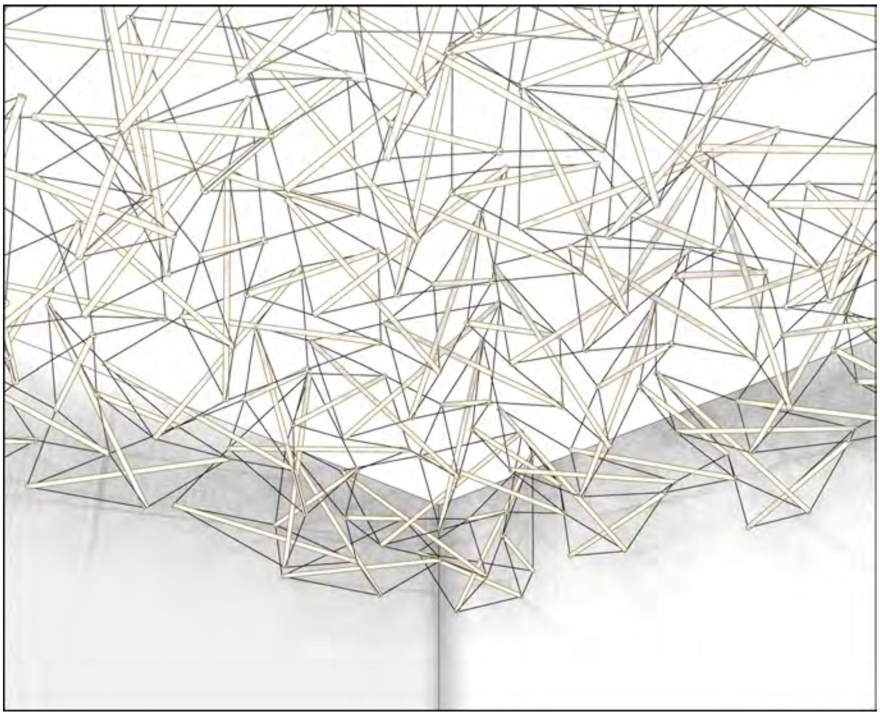

Textile Informed Structures - How to Braid a Roof

Translating the logic of textile bindings into the scale of architecture

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

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Cover: Digital visualisation of what appearance a tensegrity roof structure might take

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Abstract

There is a great variety of textiles, both in terms of the behaviour of the fibres they comprise of and the assembly methods used to construct them. Hence, the definition of textile is expanded from including only conventional fabrics to encompass all surfaces with a structure that follows the logic of textiles.[1] One can then refer to textile as a repetition of bindings, or joints, forming a non-hierarchical surface.

Analogies between classical textile assembly methods (knit, weave and bobbin lace) and structural systems are studied in this research. Similar to the work of K. Snelson the internal structural logic of textile is identified, describing the joints used in the assembly, followed by mapping of these typologies onto structures.[13] The resulting modules are aimed to be used for the assembly of structures in the scale of architecture. Similar to the behaviour of textile, these structures have the potential to grow in all directions, depending on spatial requirements, while still retaining some kinetic behaviour.

Three concepts are proposed. Firstly, an interpretation of the general assembly method of textiles combined with the theory of platonic solids, resulting in a scissor-like structure. Thereafter, parallels are drawn between woven textiles and tensegrity systems, and finally the basic pattern of bobbin lace are mapped onto reciprocal structures. These are evaluated through the application on a case project - a free-form roof structure. The final concepts yield intriguing load bearing systems that illustrate the possibility to design and construct temporary structures able to seamlessly span irregular spaces.

Keywords: Textile, Free Form, Scissor Structure, Tensegrity, Platonic Solid, Reciprocal

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1

Introduction

Textile was recognised as a material with a lot of potential, it has been widely researched throughout history and recently became a highly researched topic also in the field of civil engineering and architecture. There is a great variety of textile materials, both in terms of the fibres they comprise of as well as the assembly methods used to construct them.

The main focus of this study has been on analysing the different assembly methods used in textile structural design, defining the joints/knots/bindings used and map these techniques onto structures of various scales. This translation of a textile binding could then be seen as a building module to be used for the assembly of structures in the scale of architecture.

1.1 Definition of Textile

Textile is a wide range of materials consisting of an assembly of fibre or fibres/filaments. The assembly methods and fibres available to make a textile are numerous and thus the properties of textile are as well. The classical methods of knitting and weaving are the most commonly used in the industry but combination methods such as the knit-weave are used as well.

Textiles are often thought of as the classical fabrics used in clothes and curtains, however in reality the term textile encompass much more than that. The following definition is used by Glazzard in her PhD thesis 'Re-Addressing The Role Of Knitted Textile Design Knowledge: Auxetic Textiles From A Practice-Led, Designer-Maker Perspective':

"The term textile formerly applied only to woven structures, but is now more broadly used to encompass anything manufactured from fibres, filaments or yarns, including products using these as a 'principal raw material' (McIntyre and Daniels, 1995: 343). In some instances, the term textile encompasses items made, not using traditional textile materials, but those which use any material in combination with a traditional textile technique; for example, it may now be possible to classify some 3D-printed materials as textiles because of the structure they follow, rather than because they are produced using a yarn, fibre or filament." [1]

If the term textile is allowed to be expanded from including only classical fabrics, consisting of classical yarn fibres, to encompass a range of materials with a structure that follows the logic of textiles one could recognise textile as a repetition of joints. Therefore, in this study the term textile will be defined as non-hierarchical materials which; *are assembled by a repetition of joints through classical textile assembly methods.*

1.2 Purpose

In this study the possibilities of translating the logic of textiles onto a structure in the scale of architecture is investigated. Taking inspiration from the repetition of joints in textiles the aim is to create a module to be used when designing structures with the potential to grow in all directions depending on spatial and structural requirements.

The goal is to find new solutions for structural components with unanticipated positive features. As well as exploring a novel way of finding solutions for free form structures from another perspective, starting from textiles.

In addition to these, previously recognised positive aspects of this type of structural textile are among others:

- The possibility to create a seamless structure over an irregular space without limitations in size
- Possibilities for a resilient and portable structure
- Sustainable option due its light weight and possibility for optimisation of the structure
- The possibility to provide an efficient as well as exiting structure for the observer/user

1.3 Objective

The scope of this master thesis is to investigate how a load bearing structure could be designed using classical textile assembly methods as inspiration. The main objective is to use textile's repetition of joints and design a lightweight modular system, which could be developed to a flexible, possibly temporary, structure easily assembled, dismantled and moved.

1.3.1 Research Questions

- How can one design stable 3D architectural structures using textile knowledge as driver for design?
  - How are textiles assembled by a combination and repetition of joints?
  - What are necessary aspects of a structure for it to be a stable 3D body?
  - How can joints in textiles be mapped into a usable building module?
- What possibilities does this yield in terms of creating seamless structures able to span irregular spaces?

1.4 Demarcation

This thesis does not focus on developing new textile materials or manipulating existing materials but rather on how to translate textile structural knowledge and its logic into the field of architecture and structural engineering. The structures and concepts developed has been analysed on a conceptual level, long term effects and details of connections and the like have been neglected.

1.5 Method

By understanding the basic assembly methods of textile as well as the mechanisms behind different structural systems and stable 3D solids, the aim is to find a meeting point between material and structure. Ending in a textile inspired structure which may be scaled up to building scale.

The study is initiated with a reference study with two starting points;

- the structural oriented, focusing on analysis of mechanics of structure and different structural systems
- and the material oriented, exploring the fundamental constructive principles of textile structures, e.g. weaving, braiding, knitting.

The references are then analysed in order to find common features and possible mappings between textiles and structures. By investigating the geometry of a textile, modular pattern are discovered which are translated into different kinds of structural modules. Working in both physical and digital models there is a possibility to simulate how different concepts compare to each other. After experimenting with different meetings between classical assembly methods and simple structural systems, three concepts are proposed.

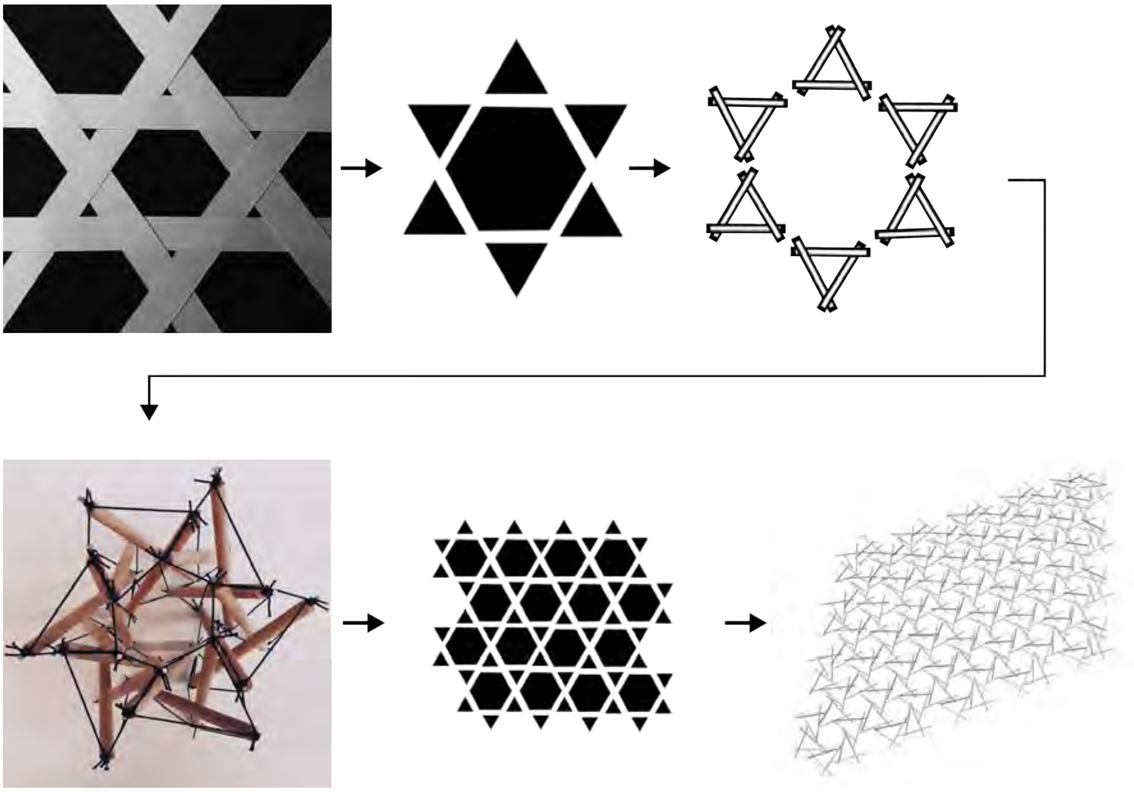

Figure 1.1: Method illustration, from the the textile joint to its geometrical interpretation and digital assembly

The concepts are aimed to be combinations of different structural systems and assembly methods, to be right in between the two fields; structural engineering and textile structural design. Each concept consists of a modular system where each module is stable on its own, as a 3D substructure, with the ability to be expanded in multiple directions. Resulting in a, similar to the textile it was inspired by, non-hierarchical surface structure.

These concept are then assessed digitally in a case study, to a large scale free form roof structure. And evaluated according to a number of different criteria e.g. material use, ease of assembly, architectural qualities etc. The aim is to produce one final modular concept which has the possibility to be composed into a full scale structure.

2

Background

2.1 Textile Architecture

Textiles are one of our oldest building materials and have been used in the earliest architecture - the dwelling for most nomadic people dating from the Ice Age to present day; the tent. Using tree trunks and branches as support and animal hides as the covering, later replaced by woven fabrics as wool and canvas. [2]

Despite the long history of textile, it has in architecture long been seen as a temporary, incendiary , fragile, unstable material with high maintenance and low performance. And even though the technology of making metal meshes and tensile structures has been available since ancient times, it has continuously been unexploited in the field of architecture. In addition to this, fashion and textile were *"traditionally associated with crafts, the feminine, frivolity, the ephemeral and the sensuous"*. This yielding a trivial view on textile use in architecture, where textile was connected to more manual vocations in contrast to the more intellectual discipline of architecture.[3]

The flexible woven mesh first emerged as a conceptual tool in the field of architecture by the thinking of Semper. In his treatise *The Four Elements of Architecture*, he redefined the wall to a spatial enclosure rather than a structural member; *"The wall is that architectural element that formally represents and makes visible the enclosed space as such, absolutely, as it were, without reference to secondary concepts."* [4] He referred to the building envelope as an example of clothing, drawing parallels between the dress and the wall, even in the common grammatical base in the German language. Built surfaces as well as textiles were by him both described as types of veiling. [4]

2.2 Textile as Structure

Many of the built examples of textile architecture today comprise a tensile textile structure. The modern era of these kind of structures began with Frei Otto in 1955 with a small bandstand, designed and built for the Federal Garden Exhibition in Kessel, Germany. He continued to design and build several more complicated canopies for various exhibitions, including the entrance and dance pavilion at the Cologne Federal Garden exhibition in 1958. [2] He explored structural properties of minimal surfaces and the optimised architectural form of tensile structures. [3]

Figure 2.1: Dance Pavilion at the Federal Garden Exhibition, photo by Yoshito Isono [5]

2.2.1 Inflatable Geometries

In contrast to the most famous structures of Frei Otto, where the textile is set in tension by cables and rods as in image 2.1 the tensile load carrying capacity of textile can also be utilised in inflatables. Inflatable geometries are made stiff by the relationship between air pressure and the surrounding envelope. By inflating an object with a volume of air larger than the envelope size the internal pressure is increased. In this state the envelope obtains stiffness and becomes a rigid object, the envelope mesh is put into a state of tension from the air pressure. [6]

The Paris based architectural office ACZ, Atelier Zundel Cristea, completed a temporary exhibition pavilion in 2012-2013 called the Peace Pavilion, figure 2.2. The pavilion is an inflatable structure made by a lightweight PVC membrane filled with air. The self supporting structure spans around 10 meters and is 4 meters high. The pavilion is manufactured as a doubly curved surface by a digital fabrication method using CNC cutting machines. [7]

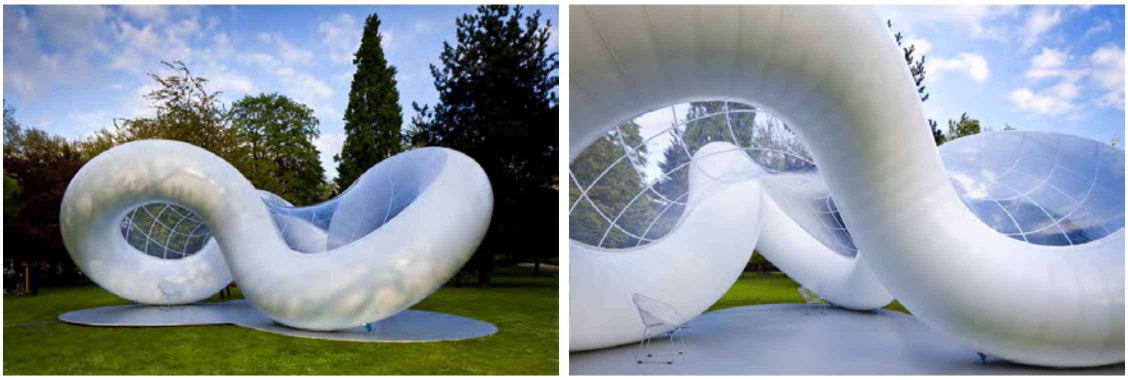

Figure 2.2: ACZ's inflatable structure; the Peace Pavilion, realized in London in 2012 - 2013 [7]

2.2.2 Textile framework

The use of textile in architecture is under expansion today. The project *KnitCandela* is an architectural example of how new technology and knit can be used in a larger scale, as framework. It is a double-curved concrete shelled pavilion developed by Zaha Hadid Architects and ETH Zurich, that has gone on display in Mexico City. The project proves that using textile as framework introduces an easily transported technique, while providing the opportunity for customising the surface appearance as the textile framework is left in its place after casting (Figure 2.3).[8]

The construction of the shell was made using *KnitCrete*, a new 3D-knitted textile technology for creating curved structures with a textile framework. The KnitCrete method yields the possibility to make a knitted framework of a non-developable digital surface. The concrete is sprayed onto the stretched fabric in multiple steps to add stiffness and load successively. The textile framework is knitted in two layers, enabling integration of different functions, such as extra reinforcements or electricity within the frame. This layering also yield extra control of the form through providing the possibility to add air pockets, as in the KnitCandela, in between the layers to decrease the amount of concrete used, within the frame. [9]

Figure 2.3: KnitCandela pavilion with the textile framework kept in place [8]

2.2.3 Structural Imitations of textile

Up until this point, the textile has been seen as a continuous mesh. However, if one would scale up a cloth into a macroweave structure it is important that the individual "yarns" between adjacent panels are aligned. To obtain this, surface mapping is used, a method used when designing cable-net structures and gridshells. [10] Simpler surface mapping method were developed for the Pompidou Metz Roof to investigate basket-weaving, or triaxial weave, on a larger scale. This method simulated flat ribbons wrapped over an arbitrary surface. [10]

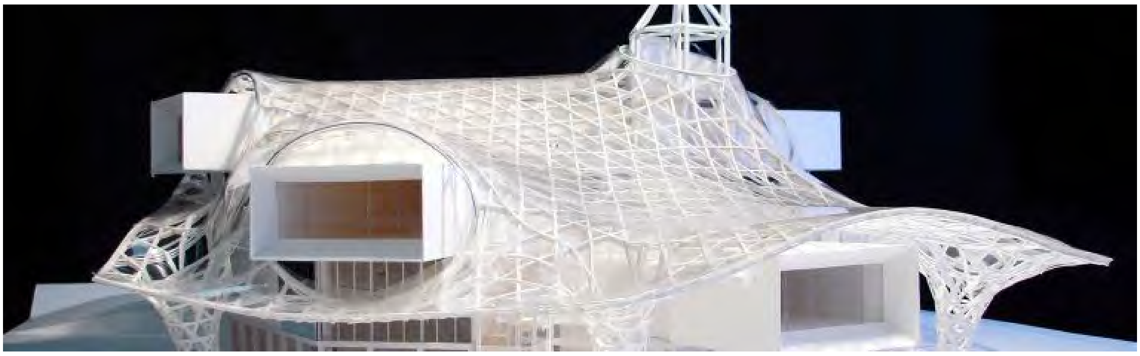

Figure 2.4: Model of Centre Pompidou Metz [11]

Further developments of these kinds of structures using only straight strips of elements tri-axially woven together to a structure has recently been presented by Phil Ayres et.al. in *Beyond the Basket Case*. Here the researchers explore tri-axial weave handcraft, kagomé, which can be extended towards a fabrication for interlaced lattice structures, supported by computational methods of representation. They present a principled work flow that support design investigation of tri-axially woven structures produced using only straight strips. [12]

2.3 Textile Informed Structure

As previously stated, textile has been used in architecture in multiple different ways; as tensile covers, inflatable geometries, textile frameworks and cable-net structures. So far, textile has been treated as either a continuous mesh or as a scaled up structure where yarns are replaced by stiff flat strips. Here follows a third interpretation of textile structures, the modular textile. Where shorter stiff elements are assembled in a repetitive manner according to the textile logic.

Reciprocal frame units can be made both as clockwise and anti-clockwise turned units. These can then be made as a reciprocal frame analogy to weave and braid systems. One early example of a reciprocal structure and weaving analogy is the bridge by da Vinci [26], seen in model images 2.5. The da Vinci bridge is an example of a plain weave interpretation where the threads have been exchanged for stiff

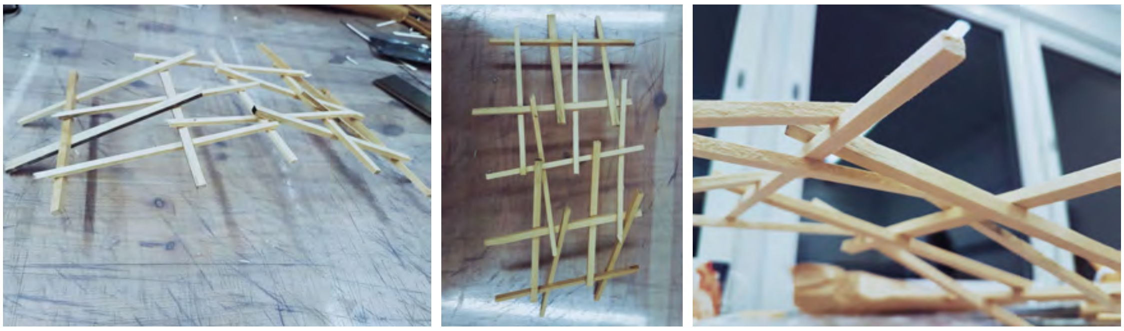

Figure 2.5: The da Vinci bridge - a reciprocal model of a weave

elements. In one direction continuous elements and in the other shorter elements which are each stabilised reciprocally by three of the continuous elements.

Kenneth Snelson, drew parallels between weaving and tensegrity structures already in 1960. [13] Using small thin walled aluminium tubes, connected to monofil tension lines, he made a planar weave tensegrity piece.

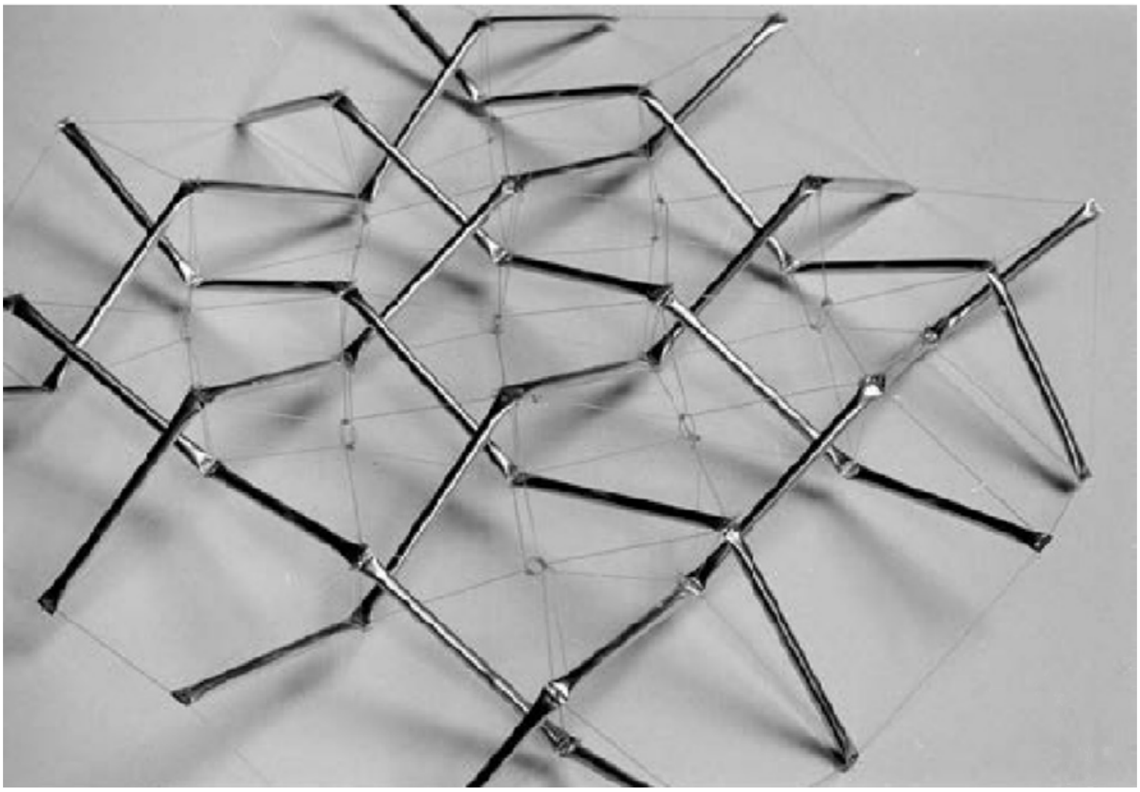

Figure 2.6: Planar tensegrity weave by Kenneth Snelson [13]

Snelson describes tensegrity as binary in the same way as tension and compression forces are binary. In all tensegrity structures a principle of altering rotational directions are found, similar to how fabric weaving works. In a weave the adjacent polygons rotate right and left, alternately similar to a chess board, as in tensegrity. This principle is fundamental to how tensegrity works.[13] This principle of alternating rotation directions will be further explored in the following chapter. In addition to the parallels between planar weave cells and tensegrity, Snelson also investigated possible three dimensional weave structures. Using polyhedrons which edges bypass one another in a helical rotation to "weave polyhedrons" he discovered three basic woven 3D patterns. [13] These kind of analogies between modular structure systems and textiles are in the scope of this research.

3

Reference Study

In this chapter a reference study of both textiles and structures will follow. Starting with descriptions of some basic assembly methods of textiles, including braiding, weaving, knitting and lace work. Geometrical concepts, both planar and three-dimensional, and their relation to structures will be explained. This is followed by a description of the basic concept of structural mechanics, stabilising a point in space. How structures are categorised according to Heino Engel is briefly explained and the chapter ends with a more thorough description of three structural concepts; scissor, tensegrity and reciprocal structures.

3.1 Assembly methods of textile

Textiles are defined as the non-hierarchical materials assembled by a textile method, i.e. repetition of textile bindings in multiple directions. Within textile design, there are materials comprised by joints, or bindings, in two or three directions within the plane. Examples of more three-dimensional textiles, e.g. textiles which can be made into a certain thickness, will also be shown.

In this section the basic assembly methods of textiles - braiding, lacework, weave and knit - will be analysed and explained. The focus being on the specific joint created by these methods.

"All material in the textile art seeks to transform raw material with the appropriate properties into products, whose common features are great pliancy and considerable strength, sometimes serving in threaded and banded forms as bindings and fastenings, sometimes used as pliant surfaces to cover, to hold, to dress, to enclose and so forth." [4]

3.1.1 Braiding

Braiding is a concept where one set of threads are interlaced with each other, one thread going under and over the other. The simplest braid, which many are familiar with, is the one of three threads, see figure 3.1. Here the edge threads go over the middle one every other turn.

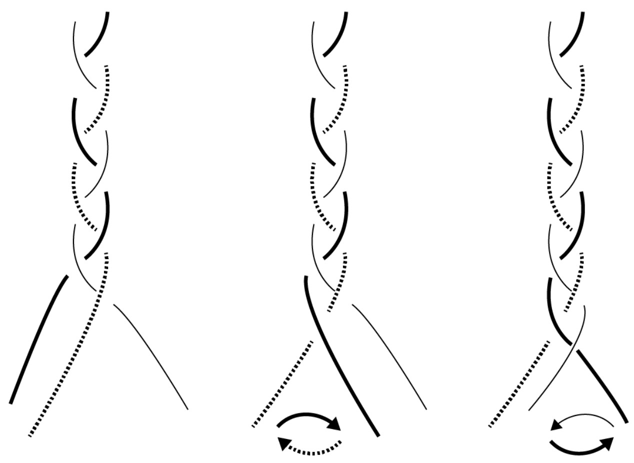

Figure 3.1: Braiding with three threads

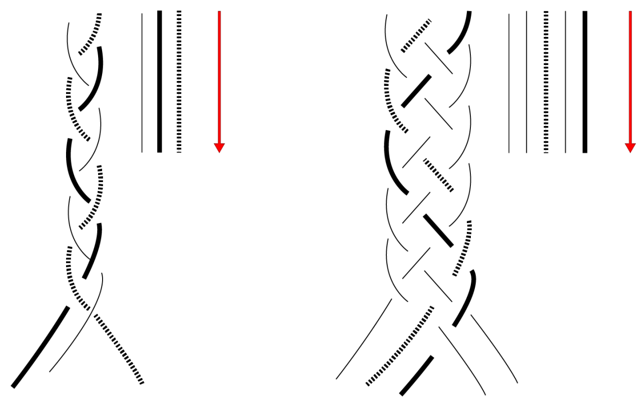

Figure 3.2: Braid of three and braid of five, red arrow indicating braid direction

This basic method of braiding can be extended into larger braids by adding any number of threads, figure 3.2. However, only three cords are active simultaneously. As the set of threads all start from the same side, or point, the threads are interlaced with an angle to its own fibre direction. However, braids serve as the strongest system of cords as the individual cords act mostly in their own fibre direction. With fibres only ending on two sides in a braid, at start and finish, they do not easily unravel either. [4]

Even though braiding in essence is based on a simple manner of interlacing threads the method offers a wide range of variations. In a braid it is for example possible to add filaments in each step, as in a french braid, see figure 3.3. This method of braiding also enables braids to serve as seams in a larger system of weaves. It then becomes active across the direction of the extension. This is due to the braid's ability to not only be efficient when stretched lengthwise. [14]

Extra filaments can also be included in a braid as inlay yarns. This is called triaxial braiding due to the three direction of threads, or the material axes, compared to the

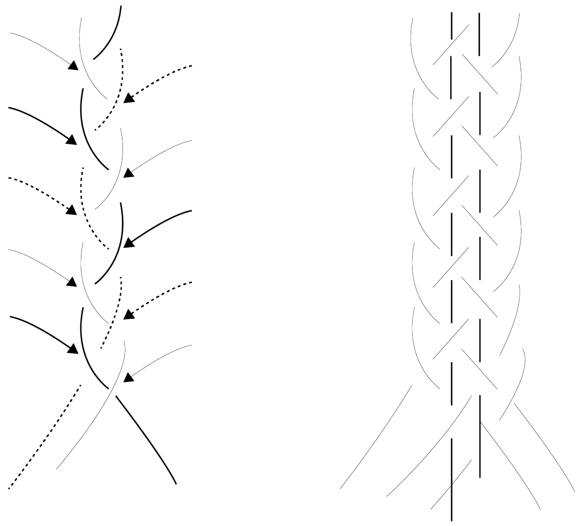

Figure 3.3: Left; French braid method, right; inlay yarns in a braid of five yarns

simpler biaxial braids, figure 3.3. [14]

3.1.2 Bobbin Lace

The knot is the oldest technical symbol known. There is a wide variety of knots, which are used for different purposes and scales. What all knots have in common is that its strength is based on its resistance of friction. [4]

Laces are made of braided, twisted and knotted threads. Lacework is often divided into two classes, needlepoint and bobbin lace. Needlepoint is, as the name suggests, made by hand with a needle whereas bobbin lace is made on a pillow with the help of so called bobbins. [4] Bobbin lace is made by braiding, passing, crossing and twisting a number of threads along a pattern. Bobbins, a kind of larger spools are used to hold the thread and add a certain weight to the thread. Pins keep the form of the pattern and the correct distance between threads. [15]

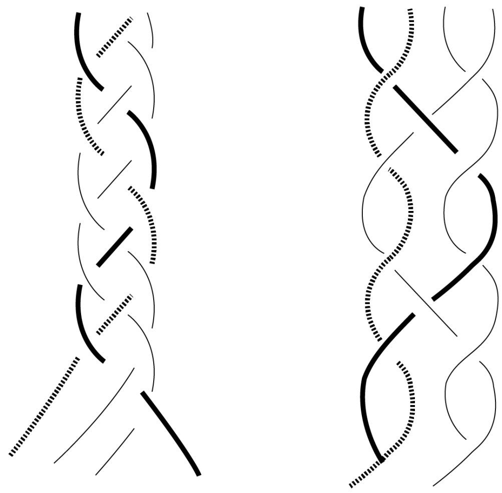

Figure 3.4: Thread path of ordinary braid of four threads (left), compared to thread path of lace braid (right)

Lace braiding is a form of braid where the braiding pattern is varied from the simple braid. In a lace braid, the thread follows a different pattern than the basic one. Where in a basic braid of four, one thread is interlaced with all other three along the braid, in a lace braid one thread may "stay" in one step, figure 3.4. In this step the four threads may be divided into two sets, only interlaced or spun together before continuing to the next step as a braid with the other pair. [14]

In a bobbin lace, there is often a ground pattern in which motifs are made. The pattern of the lace is made within the same process as the ground. These ground laces often follow a simple geometric pattern. Except for the Plain Hole Ground lace, shown in figure 3.5, two other basic ground pattern laces, Hole Ground and Tulle Ground, are shown in figure 3.6.

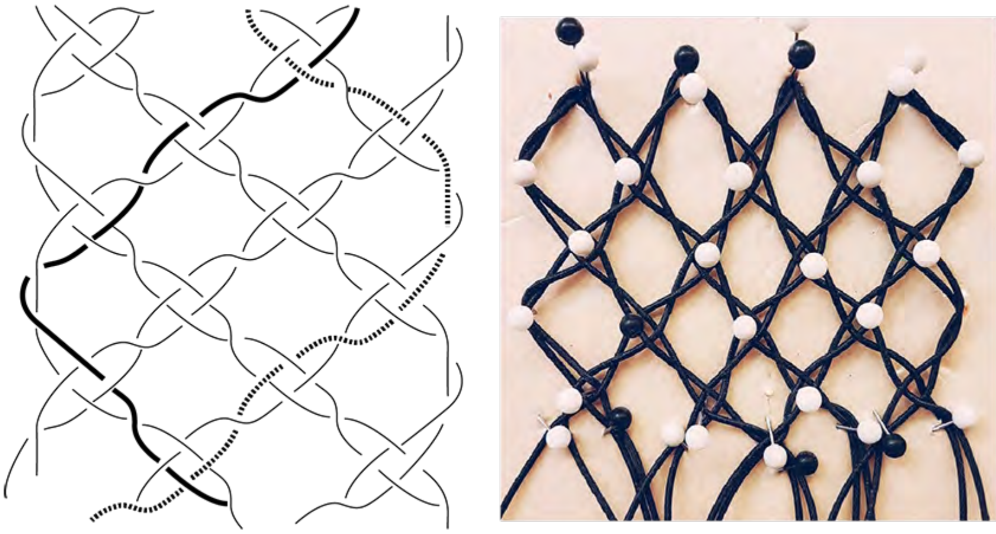

Figure 3.5: Plain Hole Ground - bobbin lace, figure (left) and lace in production with pins keeping the threads to the pattern (right)

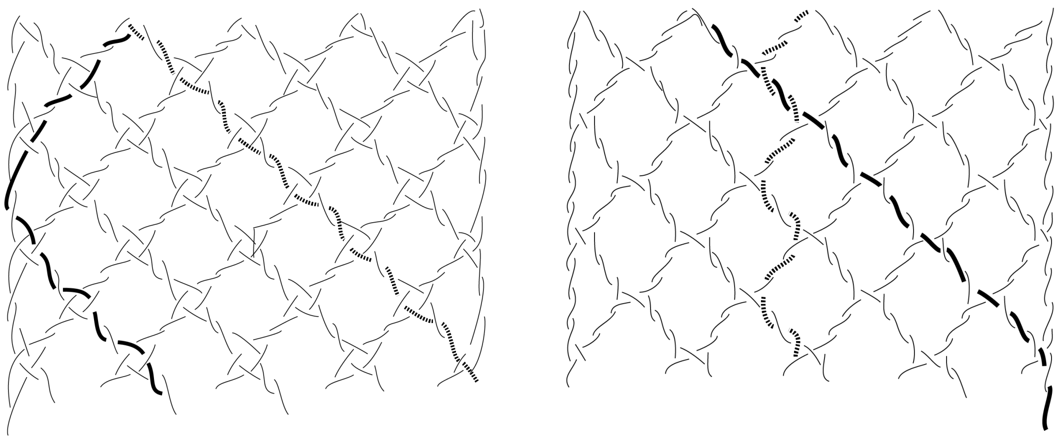

Figure 3.6: A Hole Ground lace (left) and a Tulle Ground lace (right) with two thread paths marked

3.1.3 Weave

"Weaving is distinct from knitting, netting, looping, and braiding, which are operations depending on the interlacing of a single thread, or single set of threads, while weaving is done with two distinct and separate sets of threads." [16]

The technique of weaving is based on two, or three, systems of threads which are interlaced to form a fabric. The threads that run along the fabric are called the warp. Transverse to these threads there is the filling thread called the weft, which runs across from side to side. A weave is constructed by a repetition of the weft thread going over and under the warp. This manner of interlacing threads compile a weave, see figure 3.7. [16]

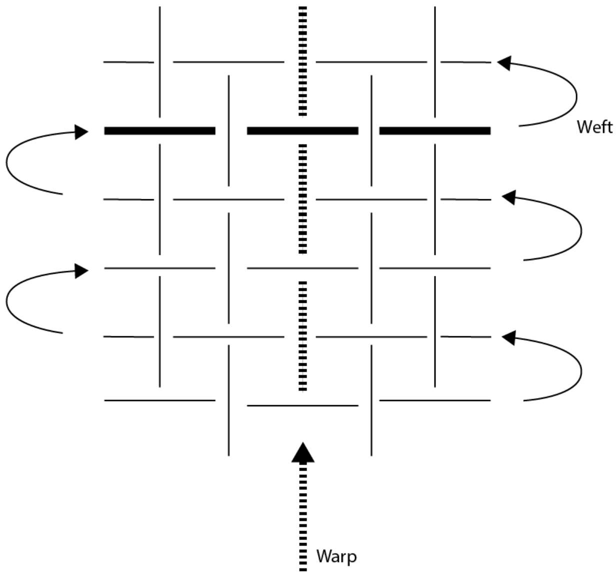

Figure 3.7: Warp and weft direction in a plain weave

There are many types of weaves; plain-weave, twill-weave and satin-weave among others; where the pattern of the weave is the defining factor. The plain-weave, is the basic weave where the weft thread crosses over one and under one warp thread in a right angled regular manner. In a twill weave on the other hand the pattern varies, figures 3.8 and 3.9. On a twill cloth diagonals can be seen. These are created when the filling threads crosses over or under more than one thread is a decided pattern. William H. Dooley explains it as:

"In this class of weaves the filling yarn or threads pass over 1 and under 2, or over 1 and under 3, 4, 5, or 6, or over 2 or 3 and under 1, 2, 3, or 4, or over 4 and under 4, 3, 6, etc" [16]

Most weaves are, as explained above, constructed by two sets of threads, usually perpendicular to each other. The direction of these two sets of threads form two axes in a weave. However it is also possible to make a weave with three axes, thereby consisting of three sets of threads (right picture in figure 3.9.

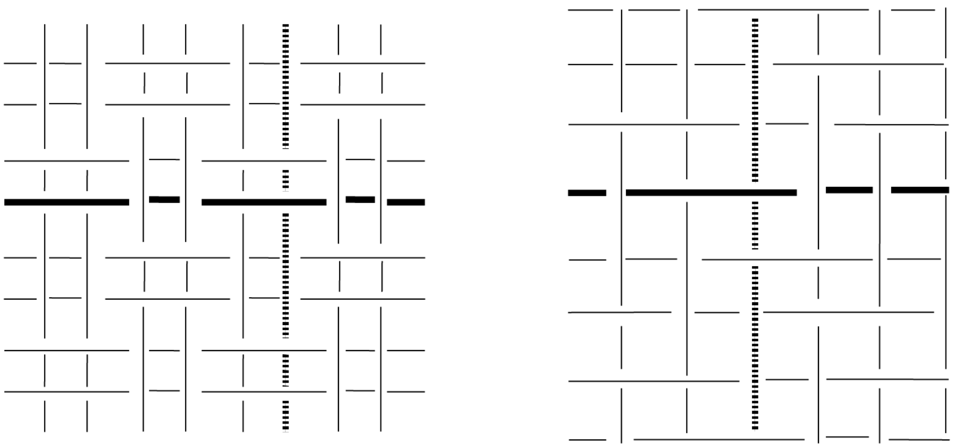

Figure 3.8: Double weave and twill weave

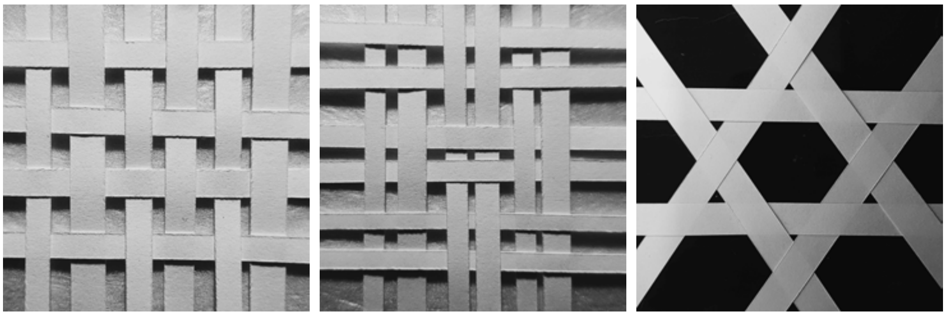

Figure 3.9: Images of plain weave, double weave and triaxial weave

Digital interpretation of a weave In "Tensegrity, weaving and the binary world" the weave is modelled digitally. Working with the two fundamental fabric weave structures; the plain weave and the tri-axial weave, here referred to as "Kagome". It can be modelled as a modular repetition with one weaving event; two filaments crossing and in contact with each other. The weave is designed by five basic cells;

- Two-way cross unit,
- Three-way triangle unit,
- Two-way plane weave unit,
- Three-way hexagon weave unit, and the
- Five-way pentagon weave unit.

With this definition of a cell, a weave is compiled by a repetition of cells, of either a right or a left helix. If one slides a finger along the filaments surrounding each cell, starting from the 'top' filament and moving 'down-hill' one will find that each cell alternates in direction between clockwise and counterclockwise.[1] [13]

[1]In this paper the directions of reciprocal and tensegrity modules are defined in the opposite directions.

3.1.4 Knit

"*Knitting, production of fabric by employing a continuous yarn or set of yarns to form a series of interlocking loops".* [17] Knitting is a very early form of textile assembly and is therefore a method which has *"been carried out to the highest perfection".* [15] It is understandable since only two needles and one thread is needed in the basic form.

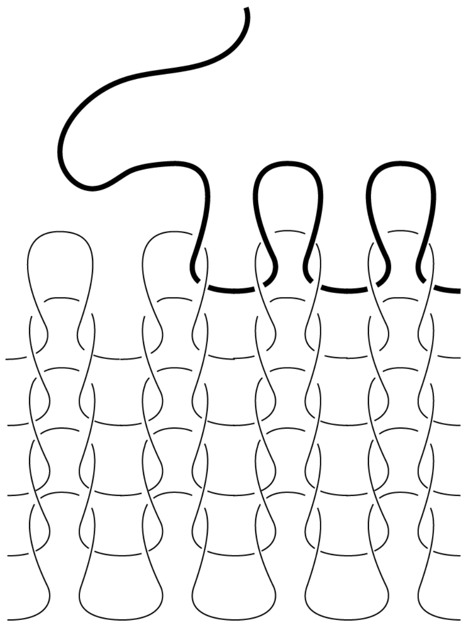

Figure 3.10: Figure of knitted structure

Knitting is typically made with only one continuous thread which interlocks in a series of loops, or loop stitches, figure 3.10. The loop stitch is a knot which when unravelling causes the unravelling of the entire system as well. [4] This configuration yield many possibilities in terms of geometries and patterns in a knitted fabric. The loops in combination with only one thread, in the classic weft knit, make it easy to add and remove loops seamlessly, figure 3.11. This alters the geometry of the knitted piece.

With different kind of loops one can create different patterns in the cloth. The variations possible are many but the simplest method of making a pattern is varying between the basic stitches; the Knit stitch and the Purl stitch. [17] The difference between them being from which side of the cloth the loop is passed, figure 3.12.

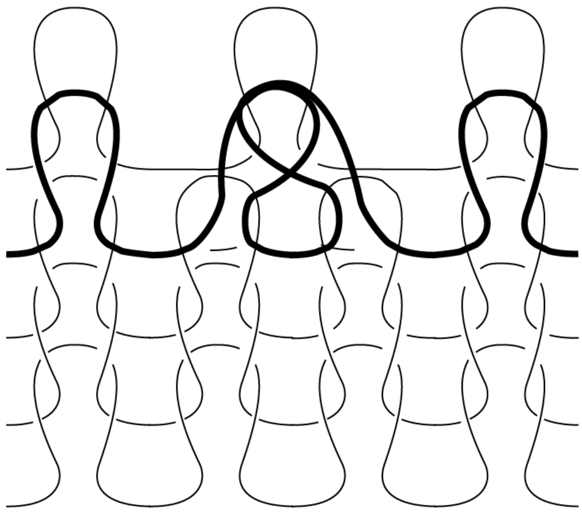

Figure 3.11: Removing loops between rows

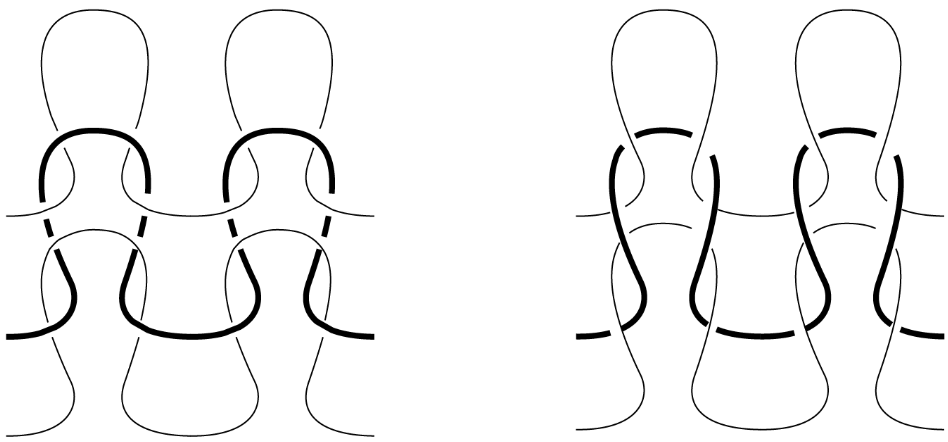

Figure 3.12: Left; Knit stitch, right; Purl stitch

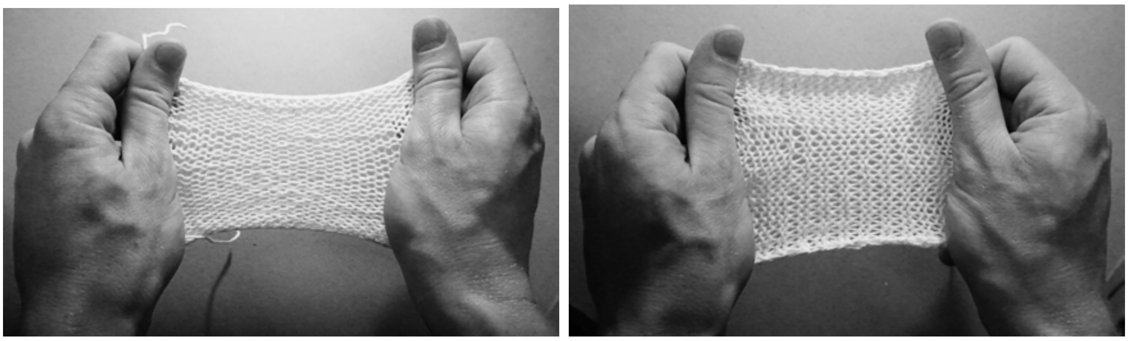

Figure 3.13: Elasticity of a knitted piece of cloth

In comparison to woven fabrics knits are, due to its loop configuration, more elastic. The elasticity also varies in different directions, see figure 3.13. This is one reason behind why it is traditionally used much in clothing. Another important reason being that the knitting structure of loops and one continuous yarn yield the possibility to make tubular sections without sewing. [15]

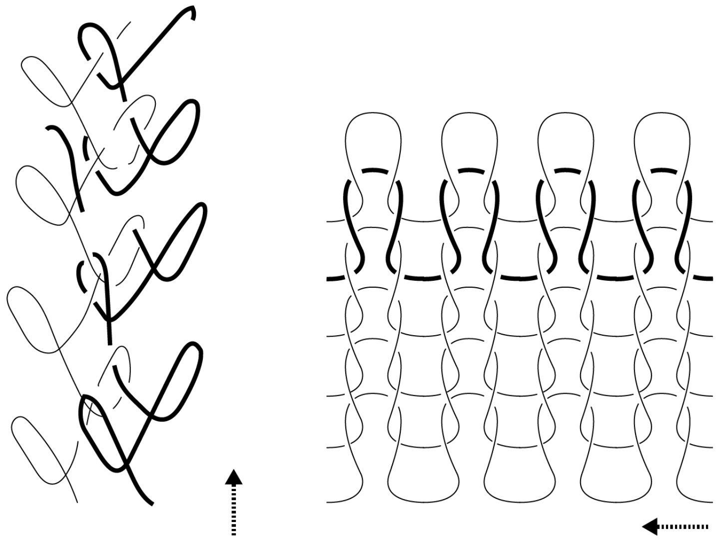

Figure 3.14: Figure of knit methods, left; warp knit, right; weft knit

There are two basic types of knits; the weft knit, or filling knit, and the warp knit, figure 3.14. The difference being the direction of the knitting process, corresponding to the warp and weft directions of a weave. In a warp knit the loops interlock along the length of the fabric. In comparison; in the weft knit they interlock in rows along the width of the fabric.

Weft knits can be made both by hand and machine. However, warp knits are only produced by machines where each warp is controlled by separate needles. These types of knitted fabrics are usually more run resistant, when one loop breaks it can cause a run in the fabric, closer, flatter and less elastic than weft knits. [17]

3.2 Geometry in two and three dimensions

3.2.1 Planar geometry

A regular polygon is a planar geometric form in which all sides have the same length and all angles at the vertices are equal - i.e. triangle, square, pentagon, hexagon etc. The number of regular polygons are infinite. All regular polygons can be inscribed into a circumference. For each increase of number of sides in a regular polygon, it is a closer approximation of a circle. [18]

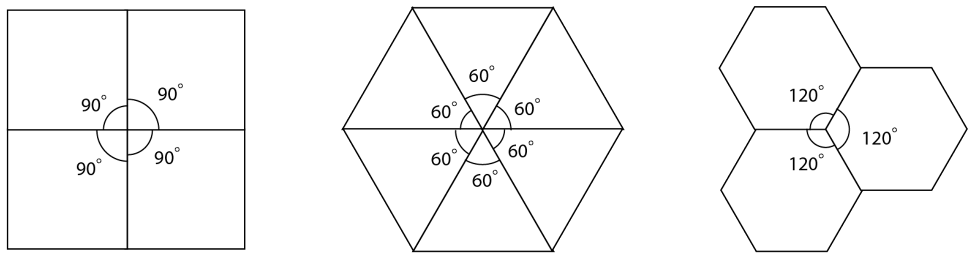

Figure 3.15: Regular polygons where the corner angle is a sub-multiple of 360 can cover a flat surface continuously

If one lays out multiples of the same planar geometry on a planar surface, regular polygons are the only shapes able to cover the surface without gaps. The only regular polygons which can be used to achieve this is the triangle, the square and the hexagon, figure 3.15. The corner angles must be a sub-multiple of 360 for the connection to be planar; i.e. 60, 90 or 120 degrees. [18]

3.2.2 Three Dimensional Geometry

Going from the two dimensional theory of polygons, the three-dimensional equivalent are the polyhedrons. And the equivalent of regular polygons in the plane are the platonic bodies in three dimensions. In contrast to the regular polygons which come in an infinite number, the platonic bodies are only five. Platonic solids are defined as the only three dimensional solids that meet the following requirements[18]:

- All faces are plane regular polygons
- All the faces and vertices are congruent
- All the vertices lie on the surface of the same circumscribed sphere
- All the faces are tangents to the surface of the same inscribed sphere and the midpoints of the faces are the tangent points

There are five regular polyhedrons; the Tetrahedron, the Hexahedron (the cube), the Octahedron, the Dodecahedron and the Icosahedron, figure 3.16. All named after the Greek word for the number of faces. This group of polyhedrons can be divided into two by their geometrical characteristics:

- Those that consist of triangular faces - Δ - Tetrahedron, Octahedron and Icosahedron
- Those that consist of 3-vertices i.e. the least number of adjacent edges - Y - Tetrahedron, Hexahedron, Dodecahedron

The tetrahedron is the only shape that complies with both groups and is therefor sometimes called "the Master Solid". [19]

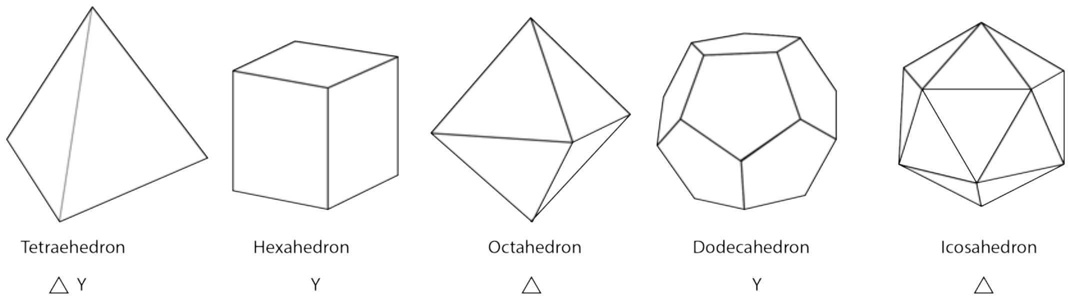

Figure 3.16: The five platonic solids. Picture redrawn from *Structural order in space* by T.Wester [19]

3.3 Stable 3D Bodies

In the following chapter the main focus will be on compression and tension forces. Some basic concepts of how to create stable three dimensional bodies which depend on the force equilibrium between tension and compression will be presented.

To make any internally stable geometry there needs to be a state of equilibrium in the geometry. According to Newtons first law; *Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed.* Meaning that if no internal force equilibrium exists, the elements will move internally and the body deform. If the body or geometry consists of a lattice structure where only pure tension and compression act it will deform when the internal equilibrium is disturbed.

3.3.1 Points in space

"In stable pure lattice structures the developed forces will be axial, i.e. pure tension or compression in the bars." One of the most basic concepts available to explain theories behind how to make stable bodies, is the concept of attaching points or nodes in space using a lattice structure. Assuming a node is free to move in all directions in a coordinate system; it can move in x, y and z-direction as well as rotate around the same axes. If it is attached to a lattice which is set at the other end, the node is still able to move in any direction perpendicular to the lattice.

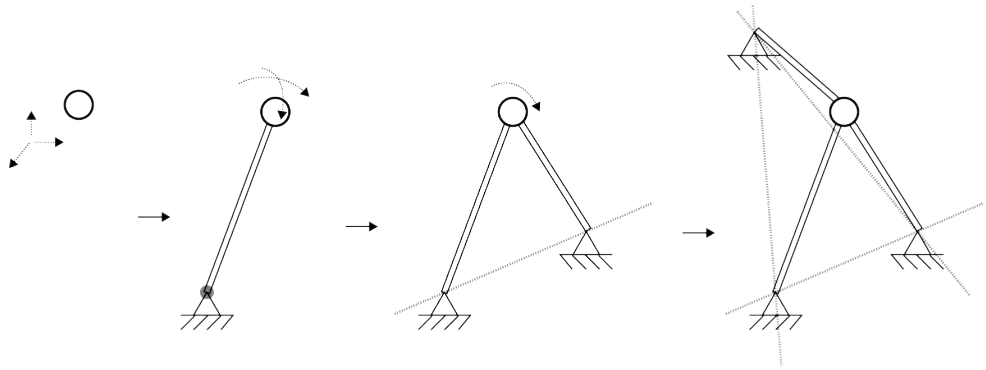

Figure 3.17: A stable point in space must be connected by three non co-planar rods

If attached to another bar, also attached to a set point in the other end, the node in question is still able to move in the direction perpendicular to both lattices. I.e it can rotate around the axis between the attached points of the lattices.

To make the node stable in space a third lattice is needed. This lattice must be attached to the node and attached on the other end at a point which is not on the same axis as the two previous. Then, the node is not able to move in any direction, see figure 3.17

The conclusion that a node must be attached with three non co-planar lattices to be stable can be drawn. *"As any external force acting on the free joint can always be resolved along the direction of the three bars, the system will be stable".* [19]

3.3.2 Platonic bodies

The platonic solids can be seen as either lattice structures where the edges are bars attached at the corners by joints, or as plate structures where the faces are seen as plates hinged at the edges. The five classic polyhedrons can be translated to these two structural types. Thus, it can be seen that the behaviour and stability of the resulting structures correspond to the two groups; Δ and $\mathbf{Y}$.

Lattice structures, as previously mentioned, contain two basic elements; the bar and the joint, see figure 3.18. The bars can take pure tension or compression and the joints distribute the loads. In these structures a node can be stabilised through connections to three nodes. The platonic bodies with triangular faces, corresponding to the group Δ, act as lattice structures.

In space plate structures, figure 3.19 the plates only carry forces in the same plane as the plate, i.e. does not work in bending. The edges of the space plate structure

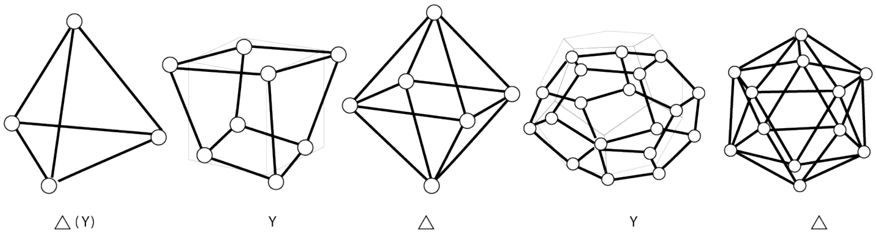

Figure 3.18: Platonic lattice structures; stable - Δ, movable - **Y**. Redrawn from *Structural order in space* by T.Wester [19]

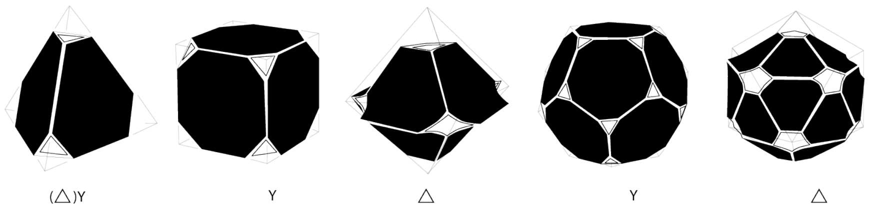

Figure 3.19: Platonic plate structures; stable - **Y**, movable - Δ. Redrawn from *Structural order in space* by T.Wester [19]

may only transfer shear between adjacent plates. A plate hinged along two lines of support can only be loaded in the direction of these supports, otherwise it will move. The plate can only carry load in the direction of its support lines. Three lines of support which are not parallel nor intersect in the same point is needed to stabilise a plate. The polyhedrons in the group with three-way vertices, Y, act as plate structures. [19]

3.4 Structural Systems

In this chapter a general categorisation of structural systems will follow, as well as more thorough explanations of the mechanisms behind tensegrity, reciprocal and scissor structures.

3.4.1 Categories of structures

Structures are usually categorised by the principle by which they carry load. Heino Engel categorises structure into five categories [20]:

- Form active structures
- Vector active structures
- Section-active structures

- Surface active structures
- Height active structures

The four first structural systems are identified by their typical mechanisms to deal with forces; to redirect them. The fifth category is a mechanism necessitated by the vertical extension of buildings. It is of concern in all previous mentioned systems, however, since it has a very particular function, it is a category of its own.

Figure 3.20: Form-active structural systems working in pure tension

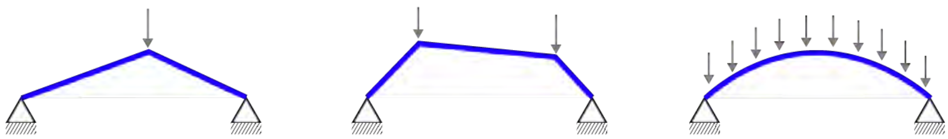

Figure 3.21: Form-active structural systems working in pure compression

Form-active structural systems carry external forces by way of pure tension or pure compression. These systems are in single stress conditions, i.e. either compression or tension. [20] In tension, cable structures such as the catenary cable (Figure 3.20, form the opposite of the arch in compression (Figure 3.21). In more three-dimensional membrane structures; a cable net in tension is the correspondent of the lattice shell, i.e. the invert of the catenary arch in compression. [21] No shear forces or bending moments are present, in theory. When designing a form-active structure, it is necessary to match the geometry of the structure to the flow of forces. And with varying external forces, e.g. snow and wind, the geometry must be able to change as well. Form active structures in tension are among the most efficient load bearing systems as they are lightweight tensile surfaces where failure by buckling is impossible.[22]

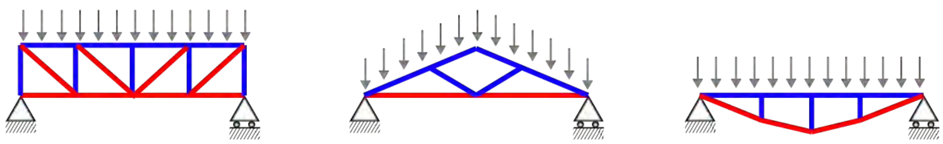

Figure 3.22: Vector-active structural systems with members working in pure tension and compression

Vector-active structural systems carry the load only through axial forces, i.e. forces acting along the direction of the structural element itself. These systems are in a "co-active" stress condition, i.e. with element in compression as well as elements in tension, see figure 3.22. [20] The lattice structures of the platonic bodies, figure 3.18 are examples of one kind of vector active structure, a framework of members which carry load only in pure compression or tension. Compared to section-active structures, the vector-active structures are in general more efficient due to the lack of bending moment. This results in a favourable relationship between the load bearing capacity and self-weight of the construction. A vector-active framework can be made as a stable structural system with a triangulated framework where the joints are pinned/hinged. [22]

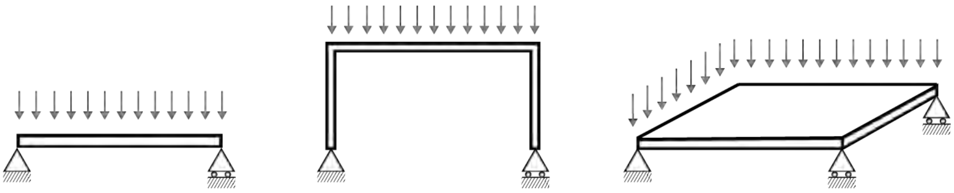

Figure 3.23: Section-active structural systems working in tension, compression and bending

Section-active structural systems , figure 3.23, carry load primarily through bending. As the name implies, the section of the structure is actively affecting the load bearing capacity as the bending moment act on the surface of each cross section of the structure, as in a beam for example. Section-active structural systems are mainly used in rectangular plans and elevations. [20]

A subcategory to section-active structures are bending active structures. These structures include tied arches from bent bars, gridshells of bent bars and shells with curved folds from bent plates.[21] Bending active structures are curved structures whose form and stiffness are achieved through elastic deformation, or bending, of the structure. The stiffness of the elements are increased through bending, and by joining several bending active elements, necessary stiffness can be achieved. [22]

Figure 3.24: Surface-active structural systems

Surface-active structural systems , figure 3.24, comprise plate or shell structures which carry external loads via a combination of membrane tension, compression and shear stress. Forces are dispersed within the membrane. Even though it is a combination of tension, compression and shear the load is carried in purely axial actions. [22] Figure 3.19 of platonic bodies as plate structures is one visualisation of a surface active structure.

Height-Active structural systems are systems without a typical stress condition where the structures act mainly as vertical load transmitter. These systems comprise, mainly, solid rigid elements in vertical extension, e.g. high rises. The main task of these structural systems is to collect loads from stacked horizontal planes and redirect or transmit them vertically to the base. In order to achieve this, height active structures must be secured against lateral stresses and firmly anchored to the ground. [20]

Hybrid structures In addition to the five structural system categories above, there are hybrids of these systems. According to Engel, hybrid structural systems do not qualify as a "unique structures family". However, a large variation of systems can be created by combining two structural systems, with dissimilar mechanisms of redirecting forces, into a hybrid structure. A precondition of a hybrid structure, according to Engel, is that the two parental systems have equal potential, or strength. Another that they are, in their new behaviour, dependant on each other. Hybrid structures comprise an infinite variety of combination possibilities, and therefore they are seen as a separate and important branch of structural systems. [20]

3.4.2 Tensegrity

Tensegrity has already been mentioned in the introduction of this thesis, as Kenneth Snelson made planar weave structures using tensegrity modules. The mechanisms behind the logic of tensegrity has however not been explained. Tensegrity is a vector active structural system, following the categorisation of Heino Engel, due to the presence of a co-active stress condition of pure compression and pure tension in separate members. [20]

In contrast to the platonic bodies; where the lattice structure that support the nodes is defined as bars which carry either in compression or tension depending on external loads; tensegrity contains element which are always in either pure tension or pure compression, independent of external loads. The term tensegrity is a combination of tensile and integrity. This was suggested by Richard Buckminster Fuller who described the system as *islands of compression inside a sea of tension.* [23] The definition of tensegrity has been concluded to; "a tensegrity is a system in stable self equilibrated state comprising a discontinuous set of compressed components inside a continuum of tensioned components." [24]

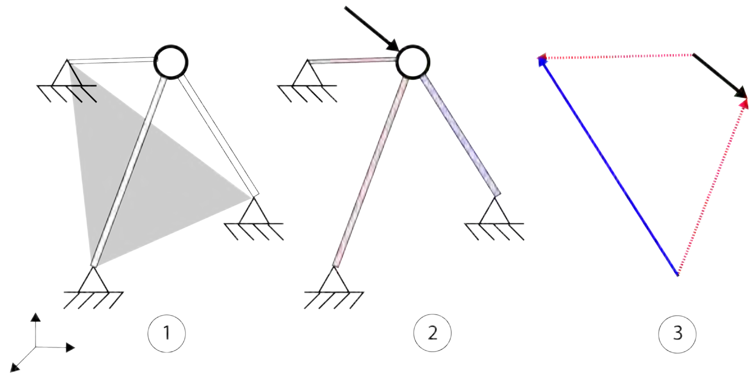

Figure 3.25: Equilibrium state of a stable point in three dimensions, under a load

Like the theory of stabilising a point in space by three lattices, figure 3.25, the same applies in tensegrity. In order to support a node "three links are sufficient to ensure the necessary condition for spatial stability". [6] In tensegrity these links are tensile elements, figure 3.26.

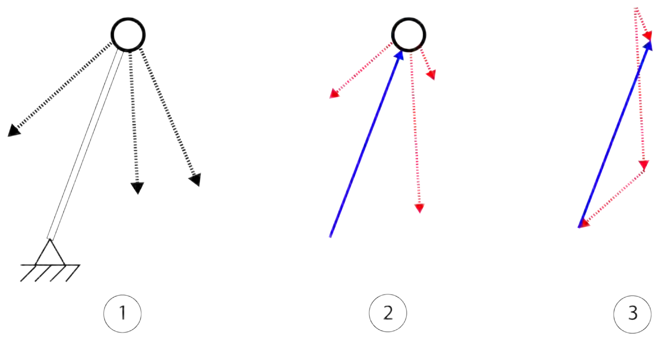

Figure 3.26: Equilibrium attained in a tensegrity structure by attaching one node on the lattice with three tensile bands

A tensegrity system comprise self-stressed elements, such that every element is either tensioned or compressed. The stability of such a system can only be satisfied for a geometry where a stable self-equilibrium can be established. To attain such a geometrical equilibrium a "form-finding process" is needed to design tensegrity systems.[6]

When form-finding a standard tensegrity module of three or four rods, the module reaches its equilibrated state as in middle and right in figure 3.27. The basic tensegrity modules are rotated slightly, the exact rotation depend on the internal relationship between the lengths of the tension bands and compression rods. In a form-finding process, this rotation yields a state of null-self stress. A condition where the lengths of each element correspond to the exact manufacturing lengths and no constitutive element is stressed. After this the elements can be self-stressed again by lengthening the internal compression elements. [6]

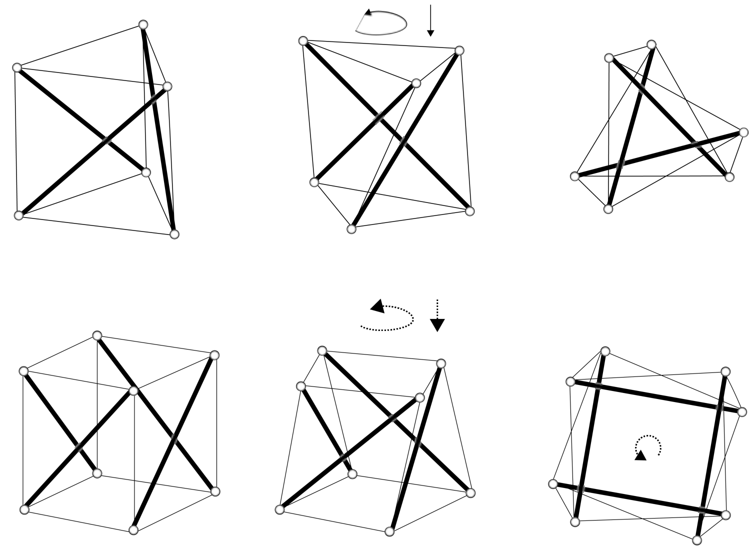

Figure 3.27: Form-finding of a tensegrity modules of three and four rods

As seen in figure 3.28, a tensegrity module is dependant on a certain rotation in the form-finding process. If not, there is no state of equilibrium between tension and compression forces in the geometry and it will warp. According to Snelson, the manufacturing of his planar weave structure was challenging due to the fact that the tension between the solid elements had to be symmetrical to avoid warping. [13]

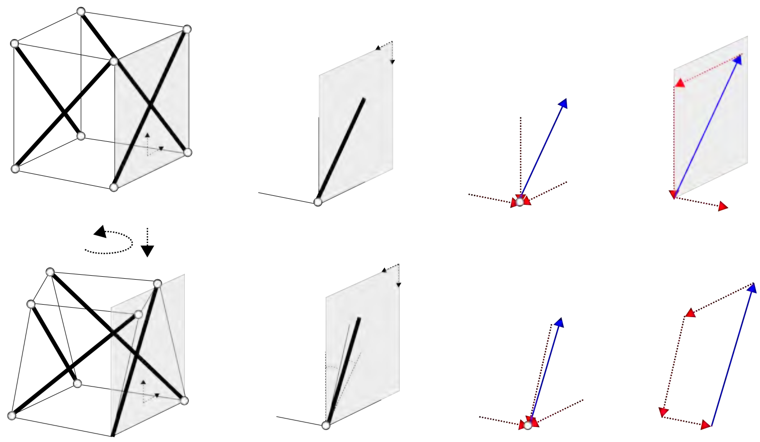

Figure 3.28: Figure and force diagram of a tensegrity module before and after form-finding to a null stress equilibrium geometry

The tensegrity module, can be turned either as a right or left helix, depending on the order in which the tension bands are connected to the rods, see figure 3.29.

The basic tensegrity modules of three and four rods both have the corresponding polygon shape, i.e. the triangle and square, as a base of the form. Starting with

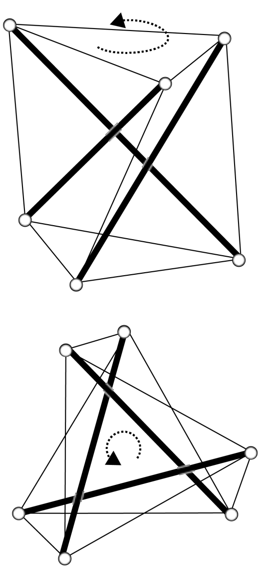

Figure 3.29: Tensegrity modules of three rods, one left turned and one right turned

the edges of a polygon as separate rods, raising one end of each rod and connecting them again by tension bands, the tensegrity module is made. Similarly to polygons, tensegrity modules can also be manufactured based on the geometry of polyhedrons, see figure 3.30. By truncating a tetrahedron, seeing the edges as rods, rotating each end of the rods in the same direction, clockwise here, and connecting the ends together by tension bands, a tensegrity tetrahedron can be made.

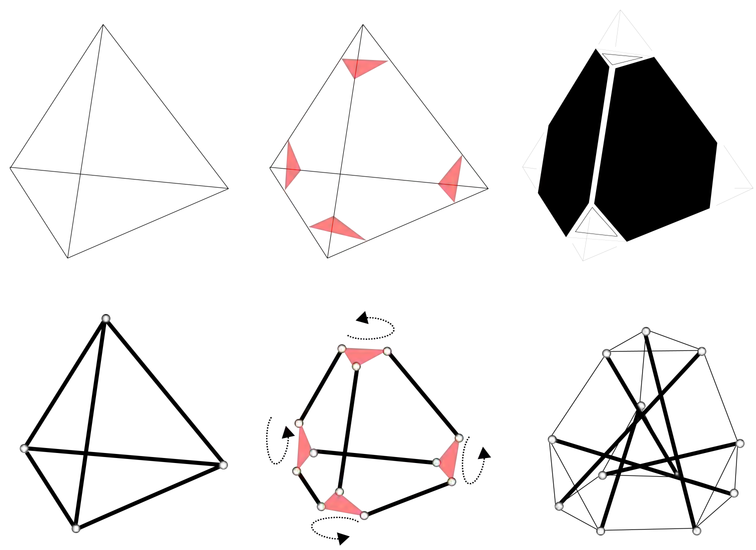

Figure 3.30: How to derive a truncated tetrahedron tensegrity geometry based on the tetrahedron geometry

3.4.3 Reciprocal Structures

The word reciprocal is defined in Oxford dictionary as; *of the nature of, or relating to, a return (in kind); made, given, etc., in response; answering, corresponding.* [25] Similar to the definition of the word, a reciprocal structure consists of mutually supporting sloping beams. The reciprocal frame, mainly used as a roof structure comprise sloping beams placed in a closed circuit, see figures 3.31 and 3.32 with a minimum of three members. The inner end of each beam rest on the next beam which in turn is supported on the next one and so on. The outer ends are supported as well by either external walls, beams or columns. [26]

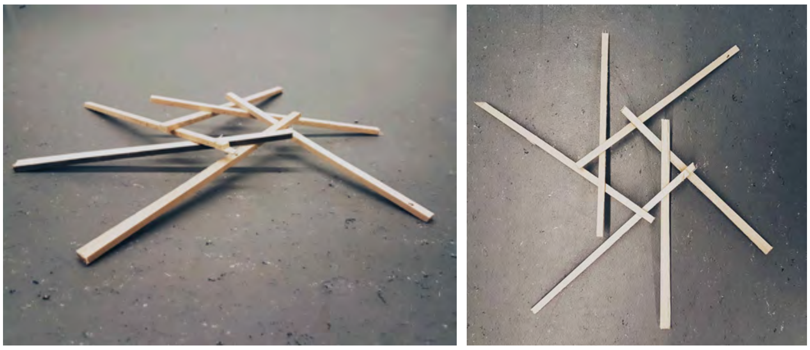

Figure 3.31: Reciprocal model of a hexagon

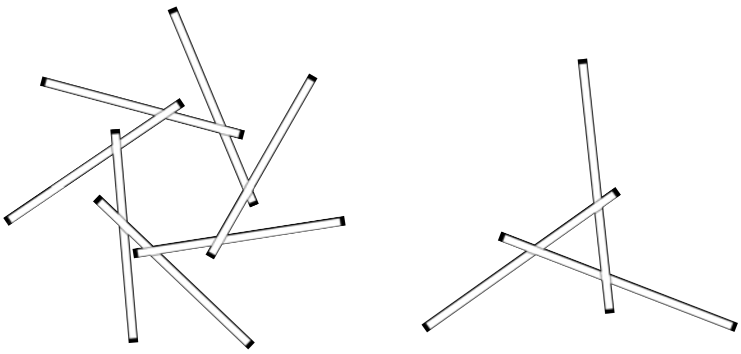

Figure 3.32: Figure of two reciprocal structures of three and seven pieces

Since the basic reciprocal frame is a circuit, in general when using reciprocal frames the most appropriate form of a building, in plan, is circular, elliptical or regular polygon. This can be seen in figure 3.32. Most buildings constructed with this technique has as follows either regular polygonal or circular plans. Using regular form gives the possibility of a modular construction of the reciprocal frames as all members are identical. [26]

In these circular units, the relationship between geometry and internal forces is complex. The size of the forces as well as the geometry of the structure will depend on the following parameters [26]:

- The outer diameter or overall span of the structure
- The inner diameter or opening
- The pitch of the structure
- The depth of the main members
- The number of members

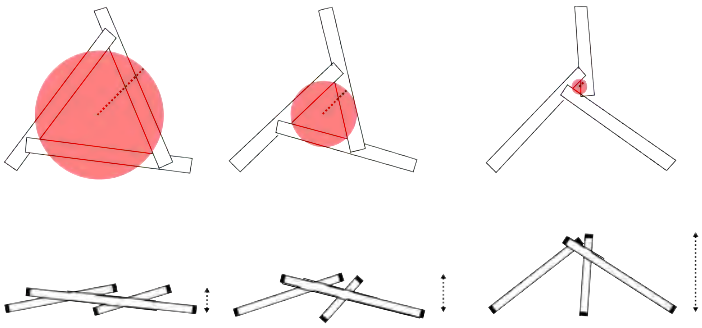

Figure 3.33: Relationship between height and inner radius in a reciprocal structure, top view and corresponding side view

The number of elements, the inner diameter and the depth of the members all affect the pitch of the structure and thereby also the height. By increasing the number of elements the height of the structure will increase. With a larger inner radius, the slope or pitch of the structure is lower, and thus the entire structure is lower, see figure: 3.33. The relationship between the depth of elements and the height of the global structure can be seen in figure: 3.34.

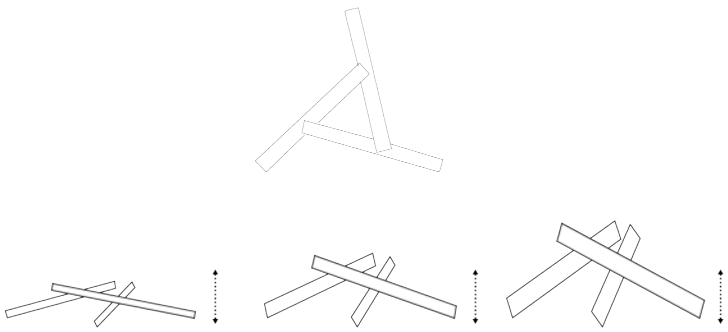

Figure 3.34: Relationship between height of elements and the global height in a reciprocal structure

Similar to the basic tensegrity modules, a reciprocal frame is also rotated in either a clockwise or counter-clockwise direction.

The geometry of a reciprocal structure, constructed as a circuit, means that the inner ends are usually positioned at a higher level than the outer ends. This arrangement makes it possible for the elements to transmit vertical compression forces, self-weight and imposed loads, along each element down to the supports. The members are, however, also subjected to bending and shear. [26] This means that the reciprocal structures are a kind of section active structures according to the categorisation by Engel [20]. Though vertical forces are transfered down to the supports, under a load the inclined geometry of a reciprocal frame may be deformed. Such, horizontal forces outwards must be taken into account for the supporting structure. [26]

The principle of reciprocal frames can be expanded into larger surface structures by combining multiple modules. Following the same principle where each element is supported by the next, the outer ends of the elements are supported by the neighbouring module instead of on the ground or a wall.

3.4.4 Scissor Structures

Scissor structures are structural elements attached together by rotational hinges. The load carrying manner of these structures depend partly on the global shape but they are locally section active due to the hinge connections. [27]

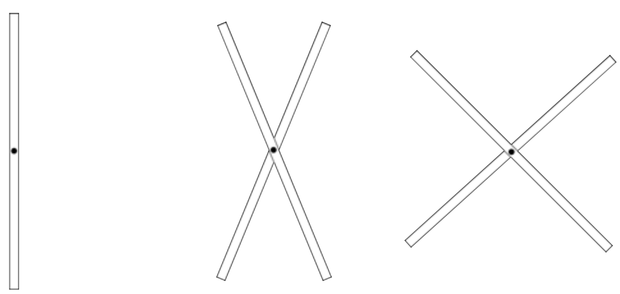

Figure 3.35: Basic scissor module

The basic scissor structure with straight elements connected by hinges in the middle of each element, as well as on the ends, yields a transverse structure, figure 3.36. If the hinges are placed with some eccentricity from the middle, a polar structure is attained, see figure 3.37. Angled elements can also be used to alter the global geometry of these kind of structures, see figures 3.39 and 3.40. [27]

Assemblies in multiple directions can be made with the addition of three-dimensional joints. In figures 3.41 and 3.42, 3D printed examples of joints, from a workshop carried out at Nottingham Trent University with Marisela Mendoza and the ArchInTex Network, can be seen.

Scissor structures, if made properly, are fully deployable structures. However the load carrying capacity of scissor structures depend on the friction in the joints between elements. If there is no friction in the joints, the structure is not stable and other forces must be introduced into the structure to keep it stable, such as cables.

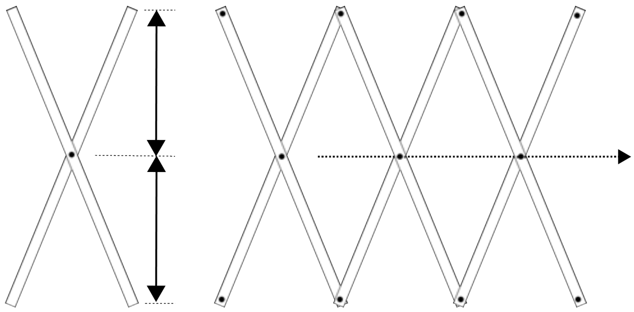

Figure 3.36: Straight elements attached at the middle yield a transverse motion

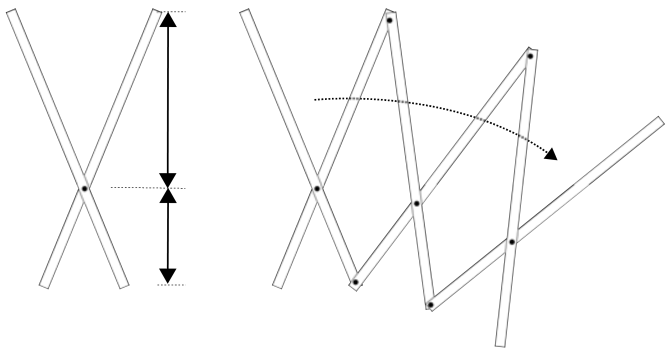

Figure 3.37: Straight elements attached with eccentricity yield polar structure

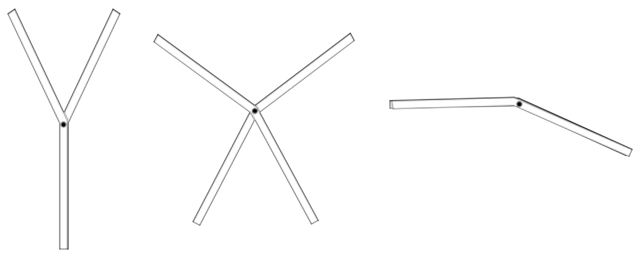

Figure 3.38: Scissor modules with angled elements

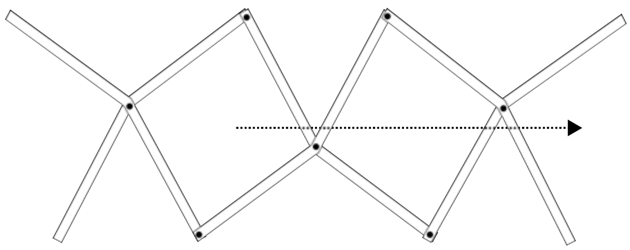

Figure 3.39: Angled scissor modules attached to a transverse structure

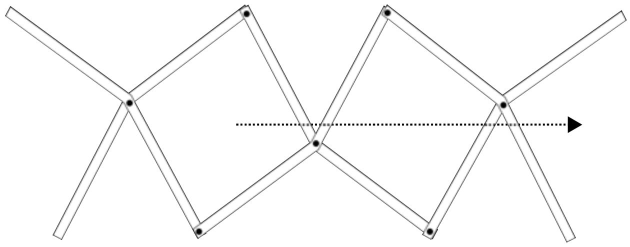

Figure 3.40: Angled scissor modules attached to a polar structures

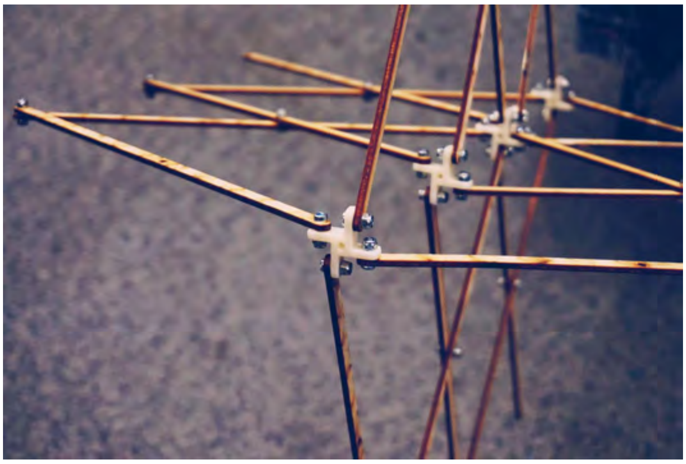

Figure 3.41: Three-dimensional joints for scissor structures (image from ArcInTex workshop at NTU, held by Marisela Mendoza)

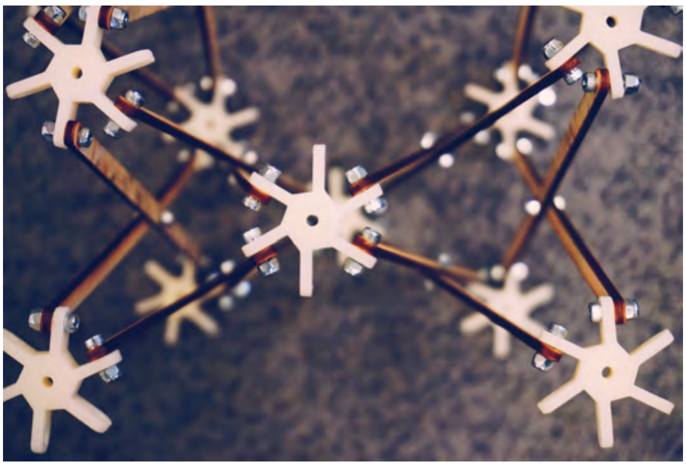

Figure 3.42: Three-dimensional joints for scissor structures (image from ArcInTex workshop at NTU, held by Marisela Mendoza)

4

Reference Analysis - Mapping Textiles onto Structure

4.1 Introduction to Analysis

In this chapter follows an analysis of both textile assembly methods and structural systems. The analysis of textile assembly is made both in a general manner and as an interpretation of the geometries found in the patterns of different textiles. The main method of analysing the structures has been by building physical models. Through the comparison between these models and the geometric interpretation of textiles, analogies between textiles and structures are obtained and defined.

4.1.1 Reciprocal and Tensegrity Structures

Before moving forward into the analysis, the similarity and connectivity between reciprocal structures and tensegrity systems should be mentioned. Tensegrity is a vector-active structure whereas reciprocal frames are section-active. Though the two do not bear load in the same way, they share geometric similarities which will prove to be important further on.

Both modules, the reciprocal frame and the tensegrity module, follow the same pattern as one edge of one member is placed over the next and so on. Where in a reciprocal frame one end of one member is supported by the next, in a tensegrity structure, these ends are connected by tension cables, see figure 4.1.

In both kinds of structural modules, the modules can be right turned versus left-turned, or turned clockwise versus anti-clockwise. A reciprocal frame module, meaning the circuit standard module, can always be made into a tensegrity module. By connecting each top end of one member to both ends of the next member by tension, as well as the lower end of both members, the reciprocal frame is turned into a tensegrity module. In what direction this is done determines which way the module is turned.

One could view a tensegrity module as an elevated, by tension, reciprocal frame of the same number of stiff elements - with the difference mainly being the structural

Figure 4.1: When realising the tensile bands of the tensegrity module (top) and thus relaxing the structure, a reciprocal frame is obtained (bottom)

system, the way in which the module carry load. A reciprocal frame is a section active structural system, according to Engels categorisation, whereas the tensegrity module is based on a vector-active principle.

4.2 General textile assembly

Given that the focus in this thesis is more towards textile as assembly methods than fibre materials, a textile is compiled by a number of joints or bindings. The repetition of these joints, in multiple directions within a plane, forms the most basic types of textiles.

4.2.1 Geometry of general textiles

In most examples shown in the reference study, the textile bindings are assembled in two or three directions within the same plane, i.e. biaxial and triaxial weaves. Most often a textile is assembled in only two directions, the warp and weft directions. This applies, in general terms, to both weaving and knitting. Where in weave there are two distinct set of threads, in knit there are two distinct directions in terms of the path the loops take.

The fact that textiles are flat non-hierarchical structures assembled in either two or three directions corresponds well to the geometrical conditions of a flat surface. As mentioned in the reference study the only polygons by which it is possible to cover a planar surface are the triangle, square and hexagon. Since the hexagon can also be seen as a compilation of six triangles, figure 3.15, the main polygons of the surface are the square and the triangle. A square has edges in two directions whereas a triangle has edges in three directions, similar to textile created by threads in two or three directions.

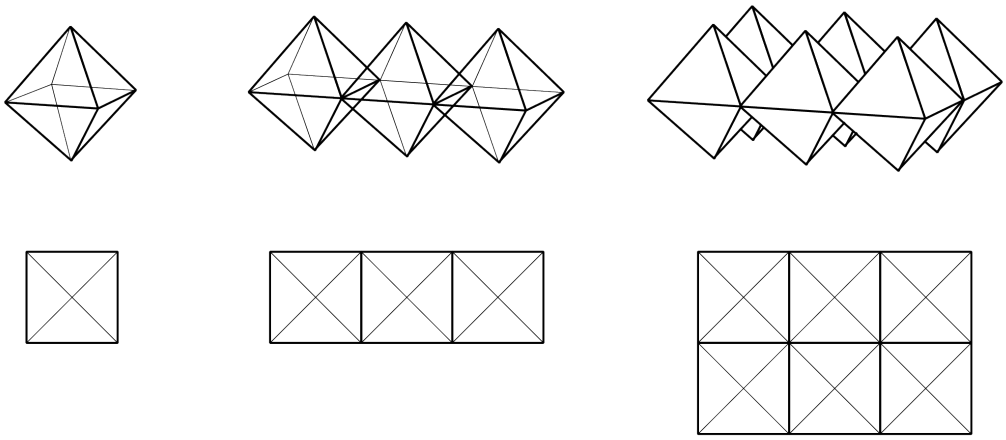

Figure 4.2: Octahedrons next to each other can cover a surface due to the square form of the cross-section

Taking this principle into three dimensions, the platonic bodies may be used. Looking at the octahedron from a top view, the outer contour lines yield a square form. Thereby, with the use of an octahedron it is possible to assemble a planar structure. 4.2

4.2.2 Octahedron Scissors

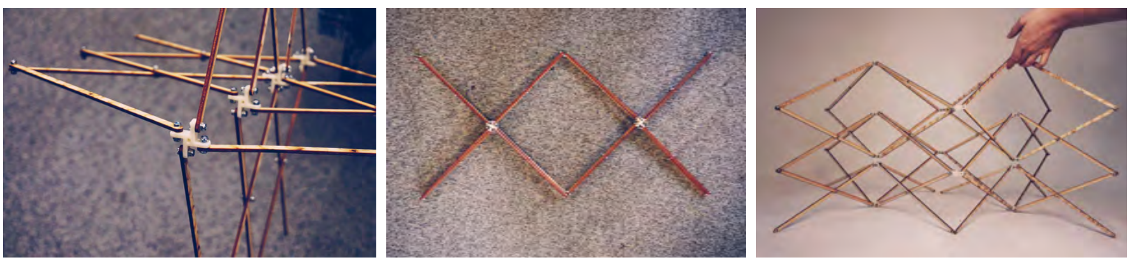

Figure 4.3: Three-dimensional joints make it possible to assemble octahedron scissor structures next to each other (image from ArcInTex workshop at NTU, held by Marisela Mendoza)

Using an edge joint in two directions, a similar structure to an octahedron can be constructed, see figure 4.3. A geometry with equal length sides, but compared to the octahedron, four edges are missing. The missing four edges means that a deformation of the geometry is possible. Thus, the shape is, similarly to tensegrity structures, deployable and its shape differs depending on relative angles between each structural element.

The octahedron-like structure can be seen as one module, which can be multiplied into a larger structure by three-dimensional joints in the edges of each module. These joints enables an assembly in two directions, thus creating an assembly that follows the textile logic, forming a surface structure. An original octahedron is symmetrical in multiple directions, thereby the assembly of octahedrons is also possible in three direction - adding thickness to the structure by adding modules in the z-direction as well.

Figure 4.4: Without friction in the joints the structure is a mechanism (image from ArcInTex workshop at NTU, held by Marisela Mendoza)

Since the scissor structures depend on friction in the joints the structure will collapse immediately if the joints are loosened enough to remove this friction. See figure 4.4.

To obtain a stable structure which does not depend on friction, the scissor structure must be stabilised in a different manner. By applying tensile force between joints horizontally, they attract each other, keeping the structure from collapsing. But this structure can fold in two directions. It is therefor not enough to only connect two joints by tension bands horizontally, but a counteraction must also be provided in the perpendicular direction. This can be obtained by applying a three dimensional tensile membrane, or multiple cables, resulting in a three dimensional force equilibrium. In the model shown in figure 4.5, the elastic cloth yields tensile membrane stress in all directions.

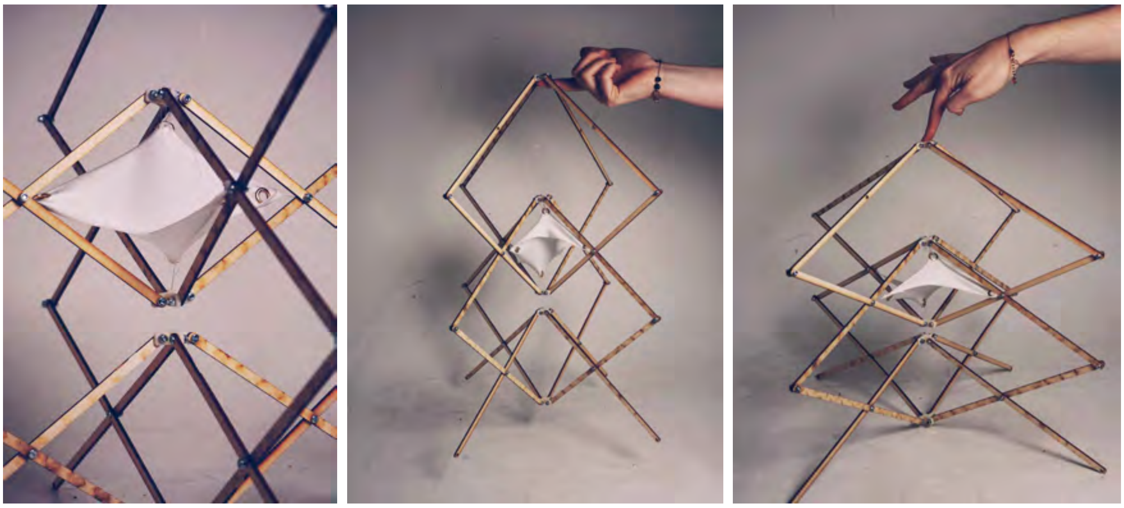

Figure 4.5: An elastic piece of fabric works as a tension membrane to stabilise the structure. With the resistance of the piece of fabric added in the middle, the entire structure gain higher resistance to applied loading (image from ArcInTex workshop at NTU, held by Marisela Mendoza).

4.2.3 Tensegrity and Platonic solids

Platonic bodies can also be made as tensegrity structures by truncating the corners, rotating the edge rods and connecting the endpoints of each rod to the neighbouring endpoints. In the resulting tensegrity structure, original faces of the platonic solid are triangulated whereas the truncation keeps its number of sides. In the octahedron example, all sides are triangulated whereas the truncation have four edges, see figures 4.6 and 4.7.

The octahedron show potential for application as a 3D weave. Observing the model from one side, the pattern of a basic tensegrity module of four rods is visible, see figure 4.8. Since the octahedron is symmetrical in multiple directions, this pattern is visible no matter from which side it is viewed.

Figure 4.6: Truncated octahedron as a tensegrity structure; truncated structure which is unstable (left) and stable structure due to triangulation of the truncated sides (right)

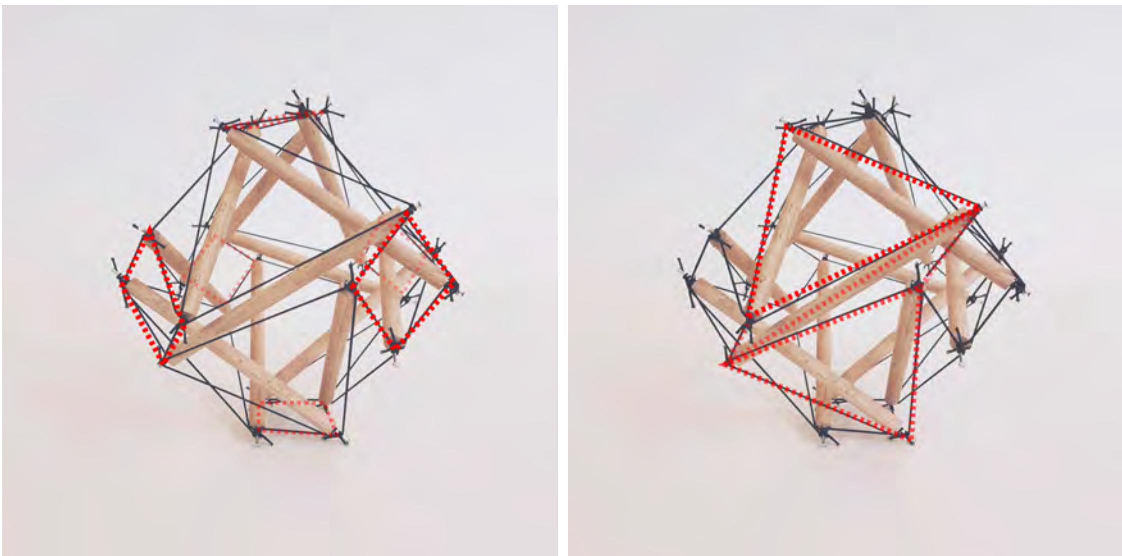

Figure 4.7: All sides are triangulated with tension bands, except for truncations which stay as squares

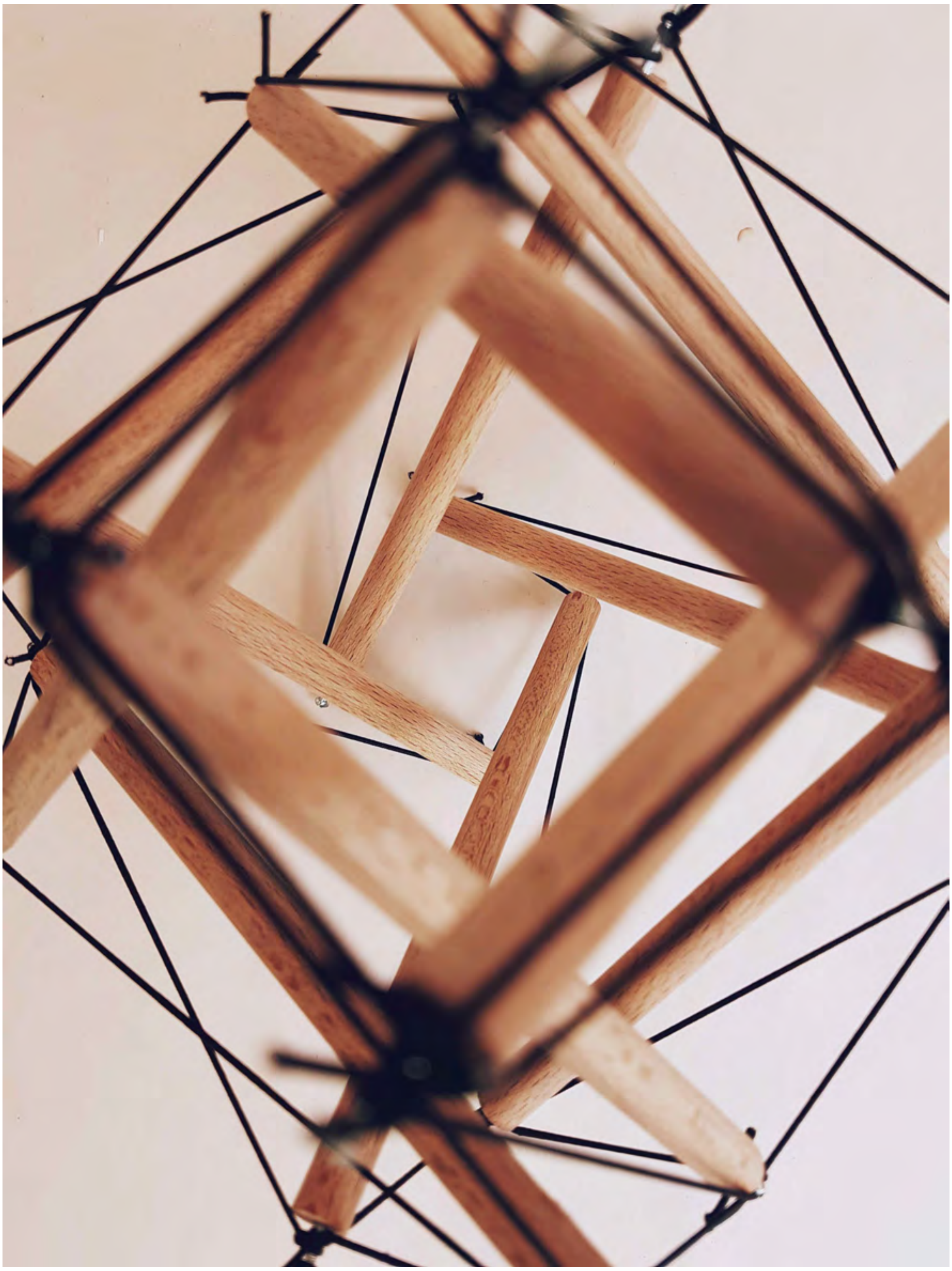

Figure 4.8: Weave structure seen in a tensegrity octahedron

4.3 Braiding Analysis

In this section an analysis of the structure found in a braid will be presented. The simplest way of braiding was used and different braiding patterns was not explored further.

Figure 4.9: Geometrical interpretation of braids

In the basic braid of three threads, a pattern of two rows of triangles can be seen. Whereas for a braid of four threads or more, both rows of triangles and squares form the pattern of the braid. As seen in figure 4.9, the edge rows in the geometrical interpretation of the braid is always triangles. For each thread that is added to the braid, a row of squares is added between the rows of triangles.

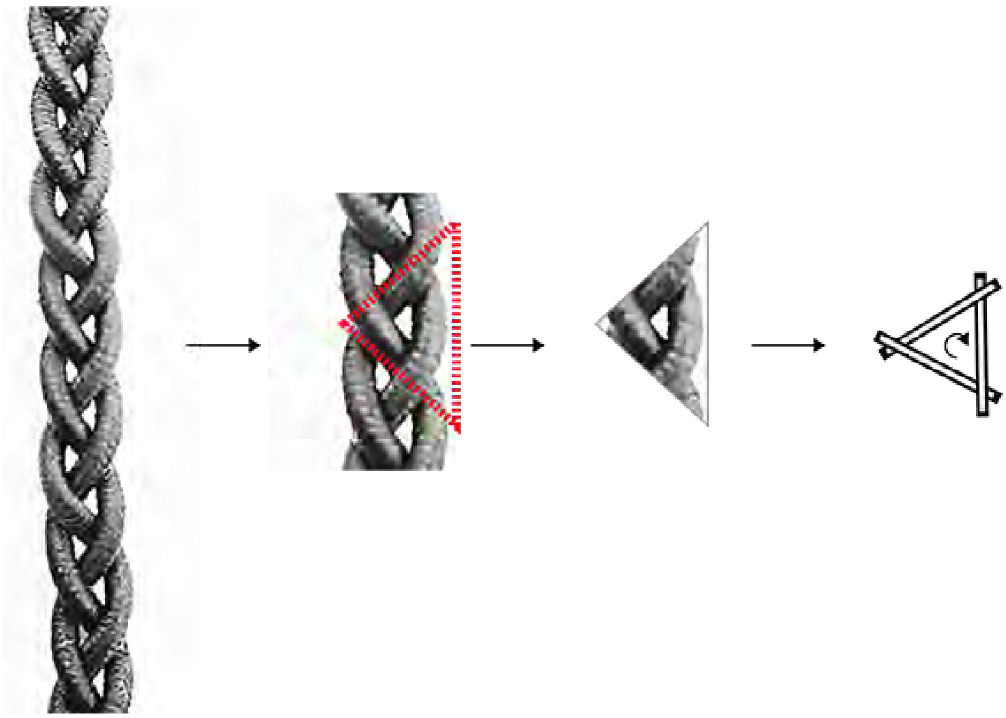

Figure 4.10: Interpretation of a triangular section of a braid

Using geometrical interpretation of braids, a braid can be divided into two kinds of sections: triangular and squared sections. The threads in a braid interlace by going over and under the neighbouring threads and then over again. If one zooms in on a braid and only looks at one of the triangular sections, as in figure 4.10, the way in which the thread goes over and under the next thread shows a similarity to a reciprocal module of three rods.

Expanding this to the geometrical pattern of a braid, each triangle could be replaced by a reciprocal or tensegrity module as in figure 4.11. When assembling these into one structure, some elements will be removed. The edge rods which are parallel to the next module's edge will serve the same purpose as the next one and thereby be unnecessary.

In a braid of three, each row of triangles are identical. However the reciprocal triangles in one row are turned differently than the other. In figure 4.11 the left row contain left-turned modules whereas the right row contain right-turned modules.

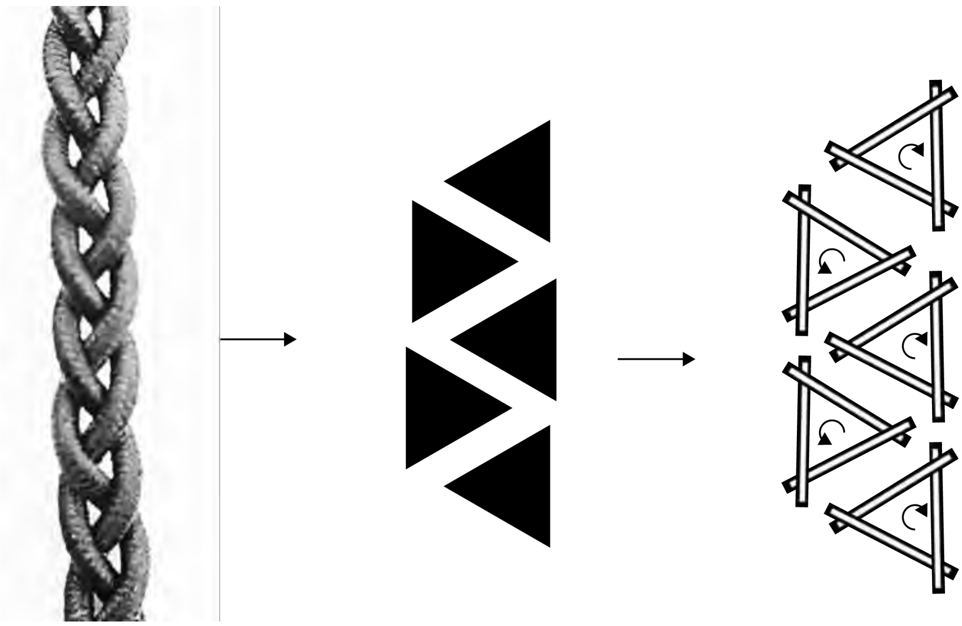

Figure 4.11: Geometric pattern of a braid interpreted to a combination of reciprocal structures

Similarly to the braid of three, braids of four or more threads may go through the same geometrical mapping to reciprocal or tensegrity structures, figure 4.12. The difference being the rows in between the edge rows which contain only squared modules. As is shown in figure 4.13, every other row contains a module which is turned in the reversed direction.

For each added branch, i.e. from three-braid to a four-braid and so on, one more row of four-lattice-structures is added.

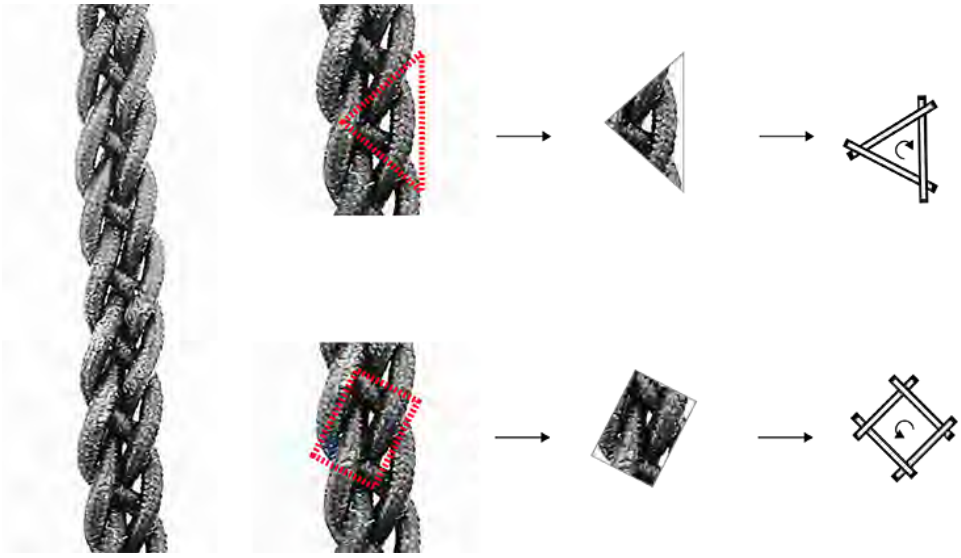

Figure 4.12: Details of a braid of four interpreted into geometric pattern

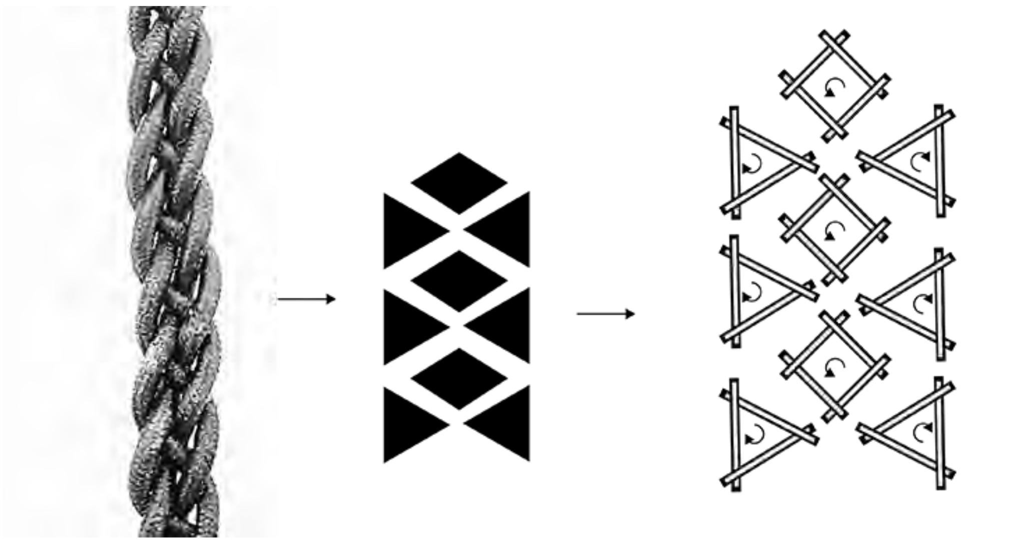

Figure 4.13: Details of a braid of four interpreted into geometric pattern

4.4 Weaving Analysis

Similar to the braiding analysis, the method in this chapter depend on a geometric interpretation of the pattern of the weave. Each geometric form represent a zoomed in section of a weave and is analysed with regard to possible parallels to structural system modules. With regard to structures the main focus of this section is on reciprocal structures and tensegrity.

In the geometric interpretations of the weave, and further on the bobbin lace, understanding of the joints used in the textile material is obtained. The repetition of the pattern visualises the repetition of joints within the textile.

4.4.1 Geometric interpretation of weaving

The three types of weaves that are studied are the plain weave, double weave and triaxial weave. In the geometric interpretations of the separate weaving techniques, the joints used are illustrated by simple geometric figures, polygons. Squares and rectangles for the plain and double weave, and triangles and hexagons for the triaxial weave. The polygons used depend on the directions of the threads. See figures 4.14 to 4.16.

In a triaxial weave the form of both triangles and hexagons are present. By analysing the pattern of the woven threads and the internal relation, i.e. which goes over and under which, the pattern may be translated to a reciprocal structure.

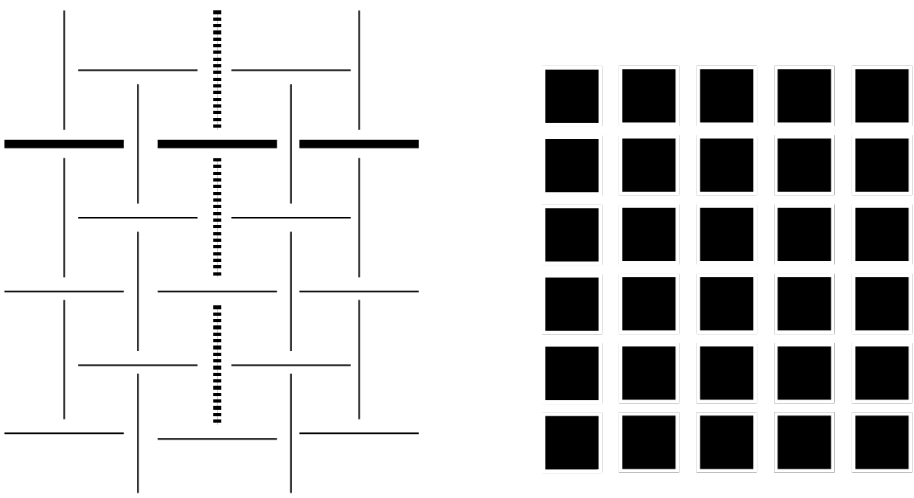

Figure 4.14: The geometric interpretation of a plain weave - 2D array of squares

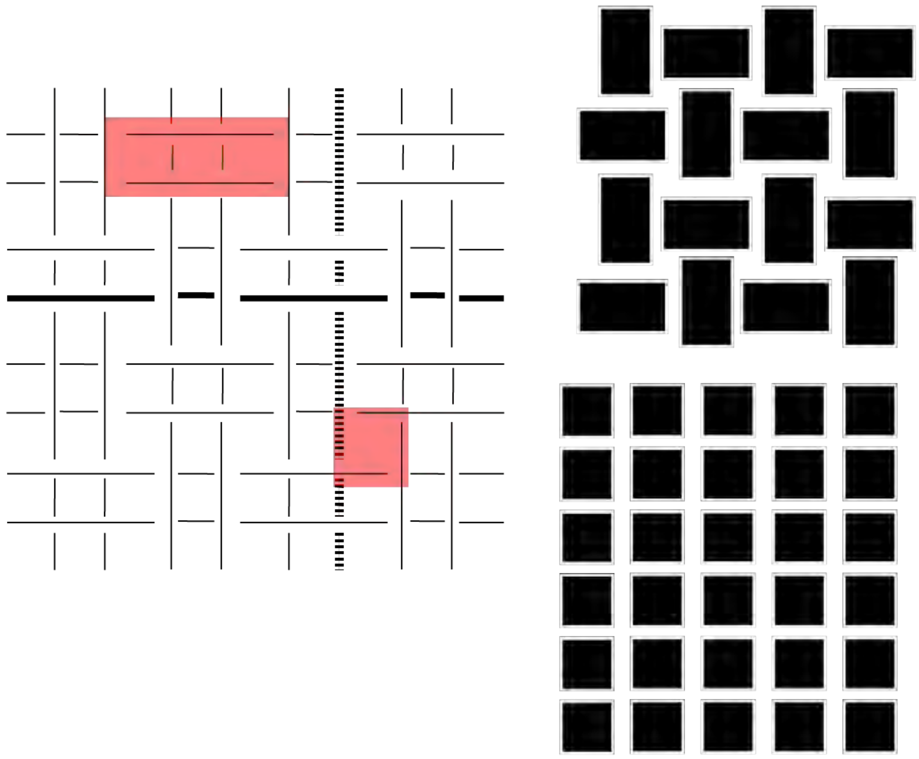

Figure 4.15: Geometric interpretation of a double weave, in two different manners

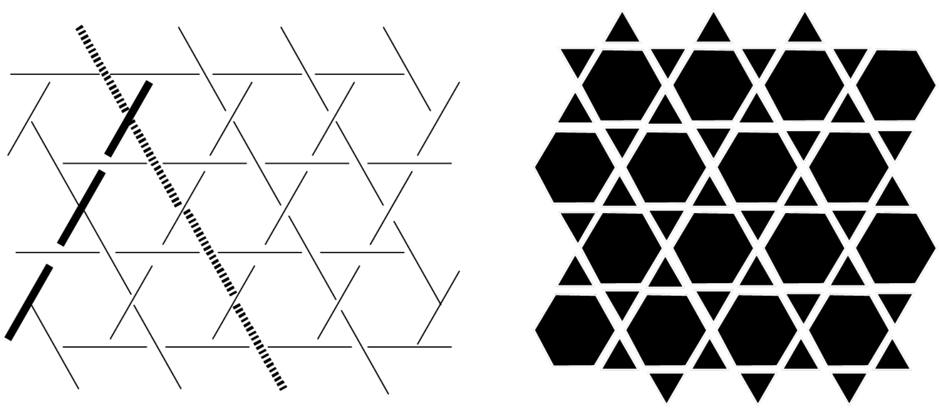

Figure 4.16: Geometric interpretation of a triaxial weave yields a pattern of hexagons and triangles

4.4.2 Reciprocal weave

Each polygon from the geometric interpretation may be replaced by a corresponding reciprocal module of the same number of elements as number of sides in the polygon.

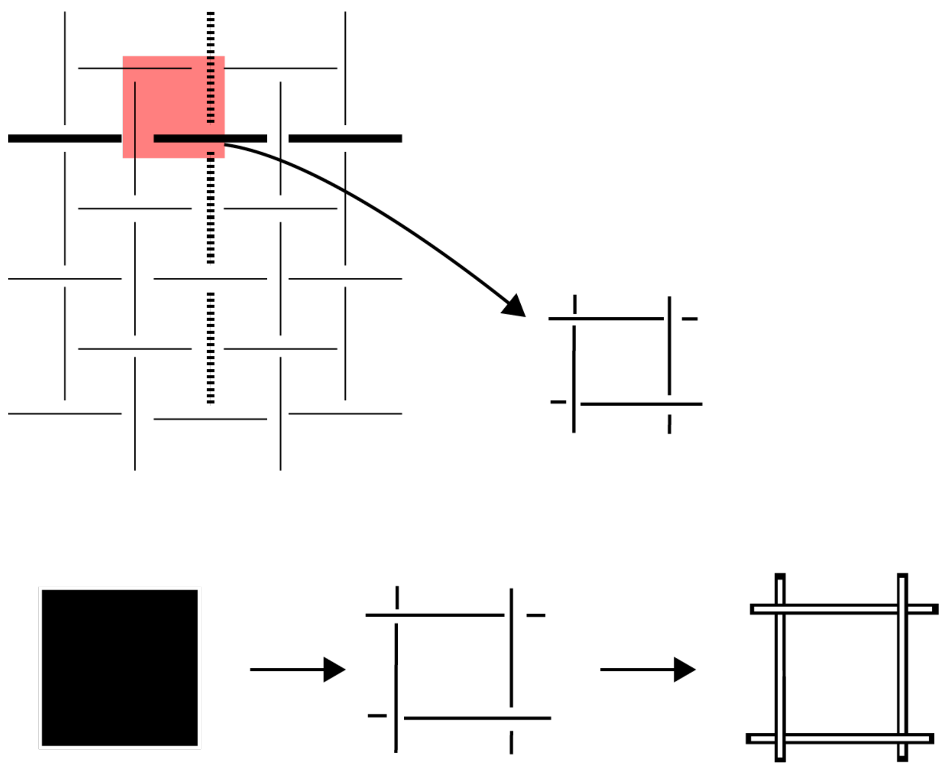

Figure 4.17: Plain weave analysis, joint resemblance to a reciprocal module

In the plain weave, the joint is replaced by a regular reciprocal module of four elements, figure 4.17. Each square represent the same type of module, however each other module is turned in reversed direction. If each module turned clockwise was visualised as a white square and the counter-clockwise as black squares, the geometric pattern would be that of a chessboard.

For both the plain weave and triaxial weave, the pattern of one module being right turned next to a left-turned comes from the fact that they share one element. In this interpretation, where for example each square is replaced by a module of four elements, the elements correspond to the threads of one joint. In the plain weave the neighbouring square, representing the next joint, contains the one thread which is the same as the previous one. See left image in figure 4.18.

In the double weave the same geometrical interpretation of squares can be done as for the plain weave and the same "chess pattern" can be seen. In a double weave however the modules can be seen as separate modules, figure 4.20.

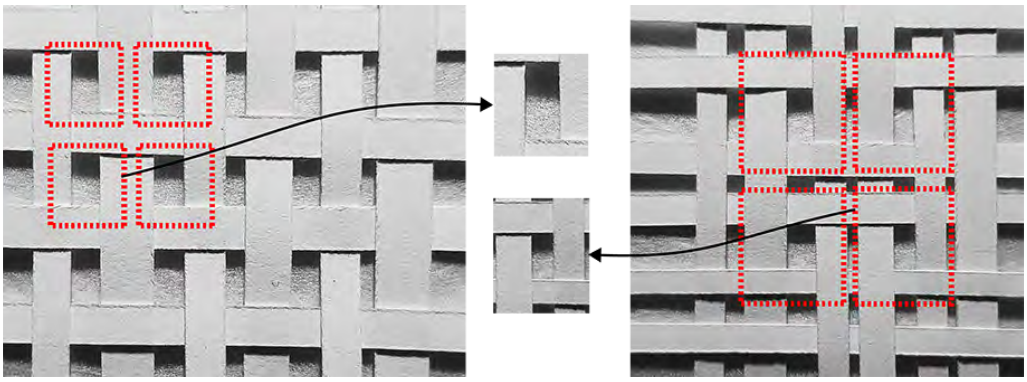

Figure 4.18: Plain and double weave structures

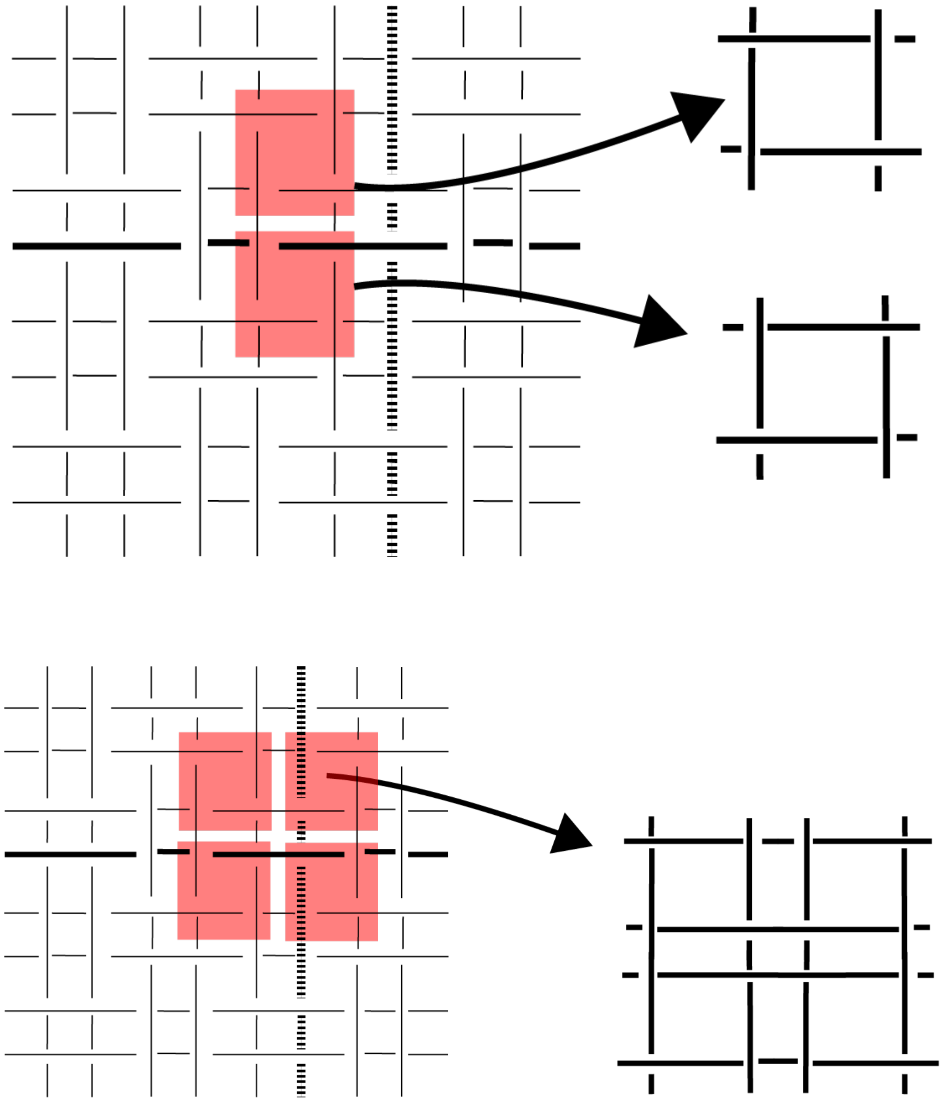

Figure 4.19: Plain versus double weave analysis, joint mapped to a structure

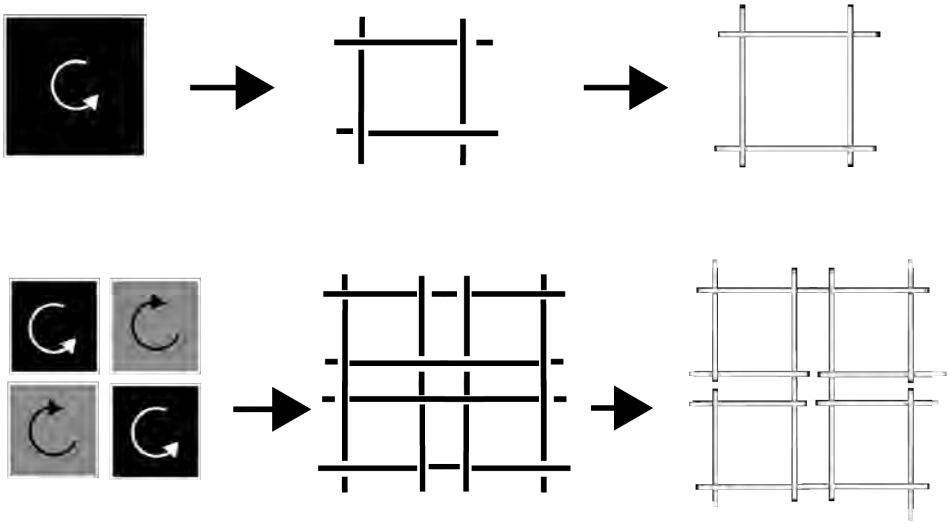

Figure 4.20: Plain and double weave joints mapped to their respective reciprocal structures

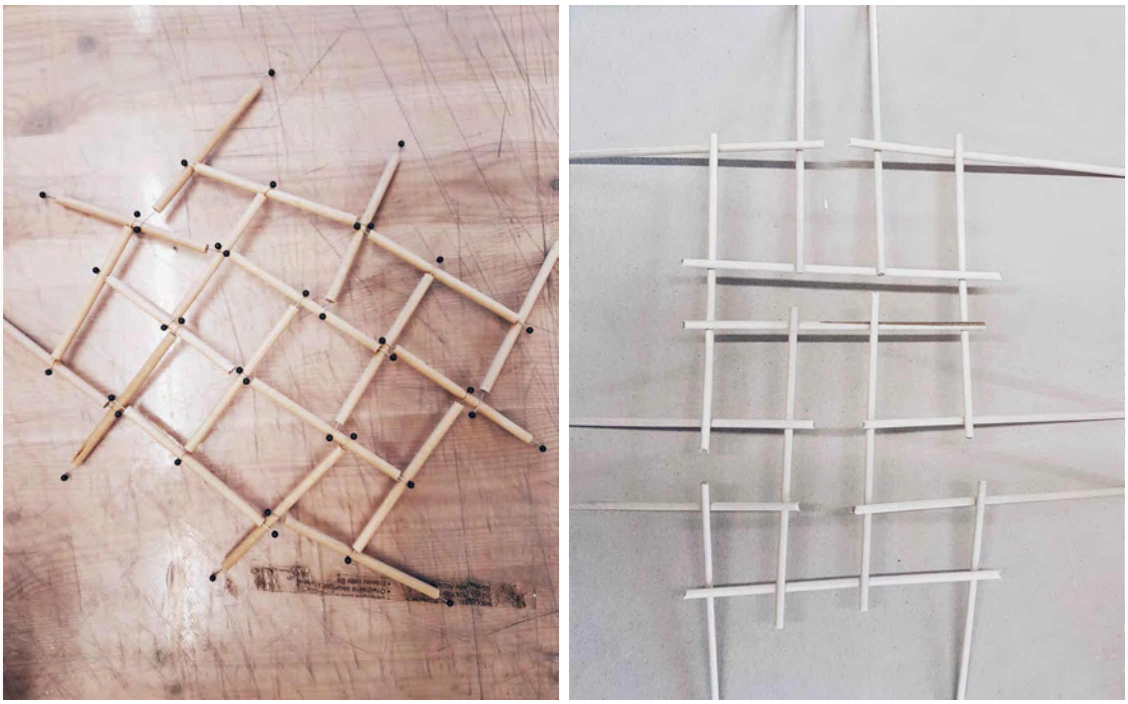

Figure 4.21: Plain and double weave reciprocal structures

The triaxial weave pattern comprises hexagons and triangles. Hence the corresponding reciprocal structures are modules of three and six elements, figure 4.22. In contrast to the plain weave, where the same module was turned differently depending on its position in the weave, in the triaxial weave the turn of the modules depend on form. All three-modules are turned in the same direction and the same applies for the six-modules. They do not, however, turn in the same direction. If the modules of three are turned clockwise, it follows that all six-modules are turned counter-clockwise.

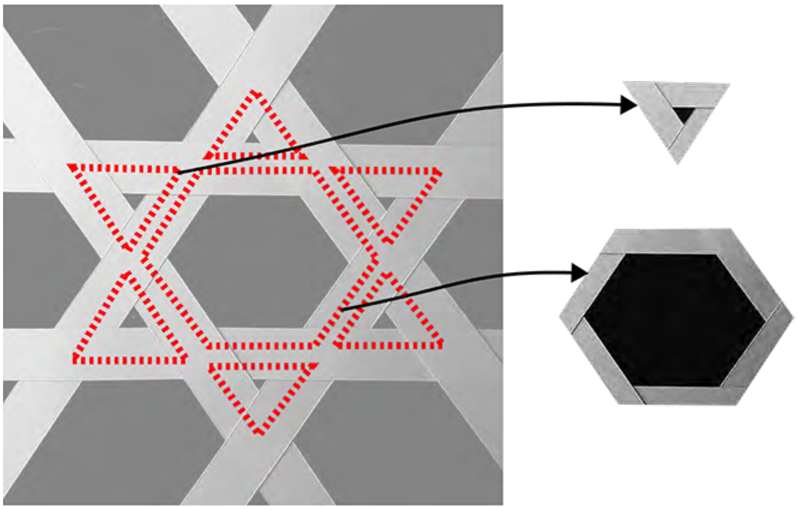

Figure 4.22: Zoom of triaxial weave joint, displaying the three- and six-parts of the full module

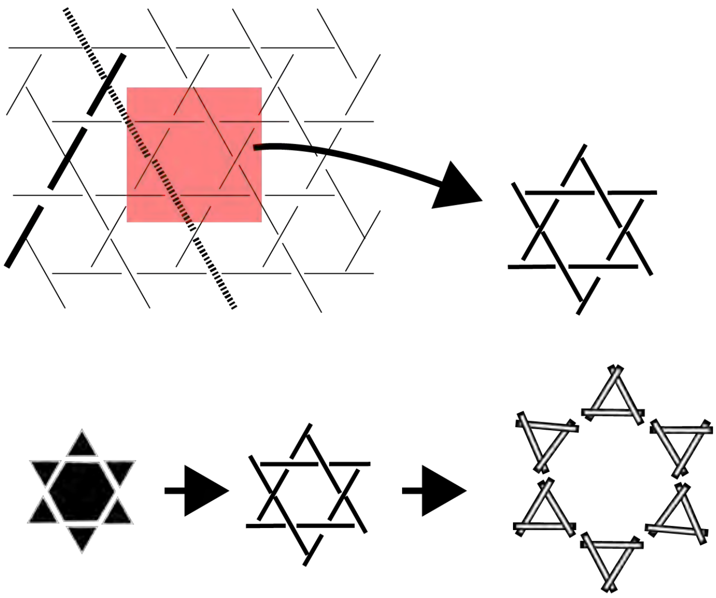

Figure 4.23: Triaxial weave analysis, identified joint mapped to a structure

Figure 4.24: Triaxial weave as a reciprocal structure

4.5 Assembly of Tensegrity Textiles

As mentioned in the introduction to this chapter, there is a relationship between reciprocal and tensegrity structures. Therefore the same interpretation which is done for reciprocal structures may be used for a mapping to tensegrity. Each polygon may be replaced by a tensegrity module. In this section a description of the principle of assembling a weave as a tensegrity system will follow.

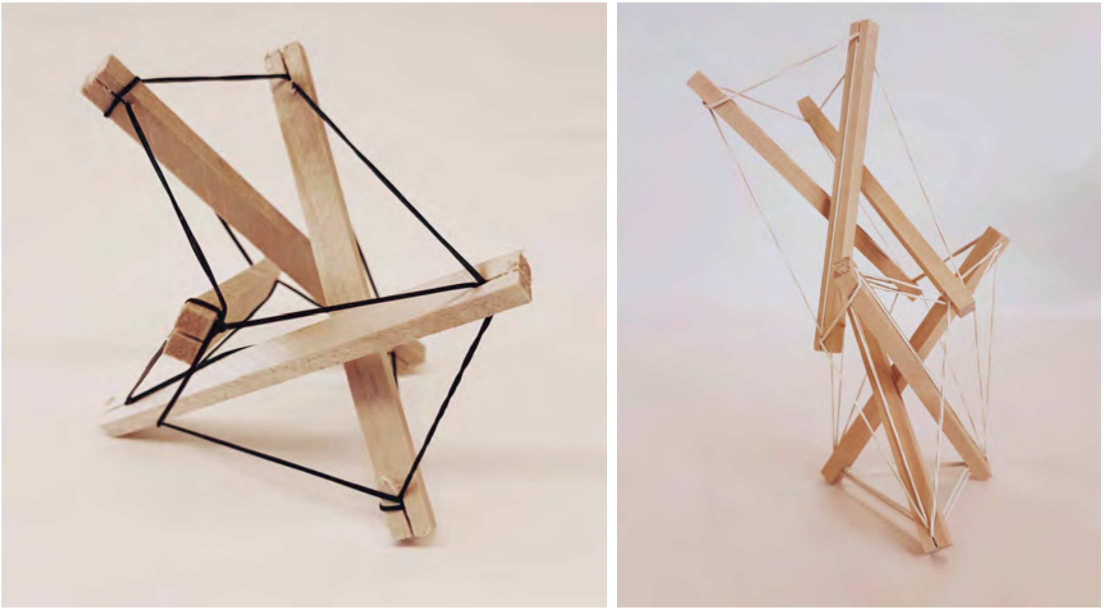

Figure 4.25: Tensegrity module and vertical assembly of tensegrity modules

Tensegrity modules can be attached to each other vertically or horizontally. To retain the tensegrity principle, where all compression elements are connected by tension bands and never touching, the modules are attached slightly rotated in relation to each other. Figure 4.25 show one way of assembling two modules of three compression elements vertically. The two modules are turned in reversed directions compared to each other. The compression elements of the module above is attached to the tension bands between the top compressive elements in the lower module.

Following the logic of the braid; divided into cells which can be mapped to tensegrity modules, each cell neighbour being turned in the reversed direction due to the interlacing of the thread; the same mapping can be made on plain weave structures. The simplest tensegrity module, the one of four, can be found in many types of textiles, foremost in the typical weave in two directions. In a plain weave one can interpret weaving cells with alternating directions. According to a chess board pattern, the direction of the tensegrity modules alternate so that each clockwise module is surrounded by counterclockwise modules on all four sides, and vice versa.

The alternating directions in a weave is already explained by the fact that the same thread is shared in multiple cells (figure 4.21). In a mapping of the weave onto tensegrity, this results in one of the compression elements being the same/shared between neighbouring modules, as shown in figure 4.26.

Figure 4.26: Weave pattern of two reversed tensegrity modules, one compression element removed when joining

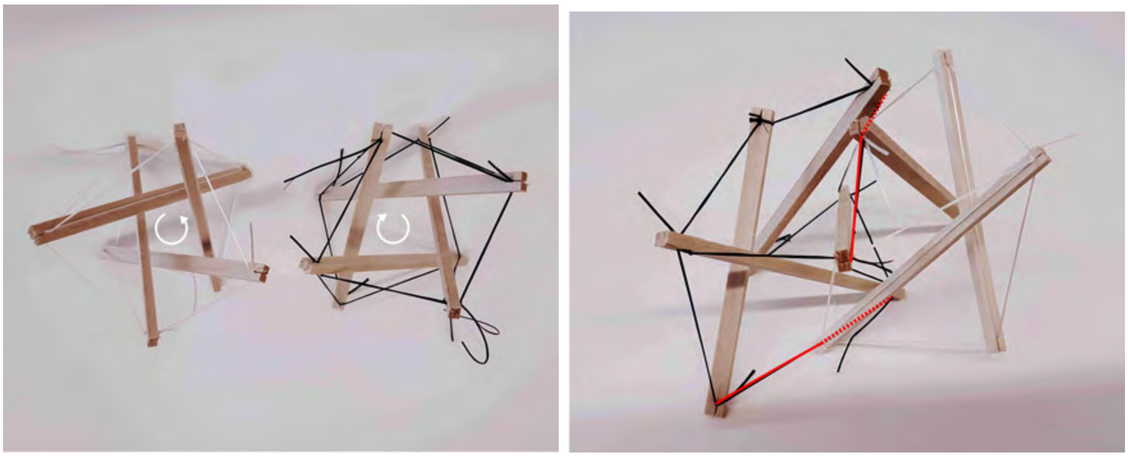

Figure 4.27: Assembly of two reverse turned tensegrity modules - one module is attached to the middle of the tension bands on the neighbouring module

The assembly of tensegrity modules is possible if compression parts are attached to the middle of the tension parts of the next module, figure 4.27. This enables the modules to "twist" in the same way as if they were individual modules. Without this twist of the module, a force equilibrium cannot be obtained.

If one attaches the modules by hinges at ends of the compression elements, it enforces the structure and each module of four lattices to take the form of a cuboid. Previous force equilibrium figure (figure 3.26) show that a regular shape cannot stand on its own since equilibrium cannot be obtained in the single module. To obtain a stable shape of this kind, a planar weave, the amount of tension in the bands must be equal. Evident in the model experiments, the same amount of tension is hard to obtain and the planar weave with hinges is an unstable structure.

The binding of a triaxial weave can be mapped in the same manner. In figures 4.28 and 4.29 the assembly of one tensegrity triaxial weave joint is shown.

From the geometric interpretation of the triaxial weave, it was evident that this type

Figure 4.28: Triangular tensegrity modules to be assembled to triaxial weave

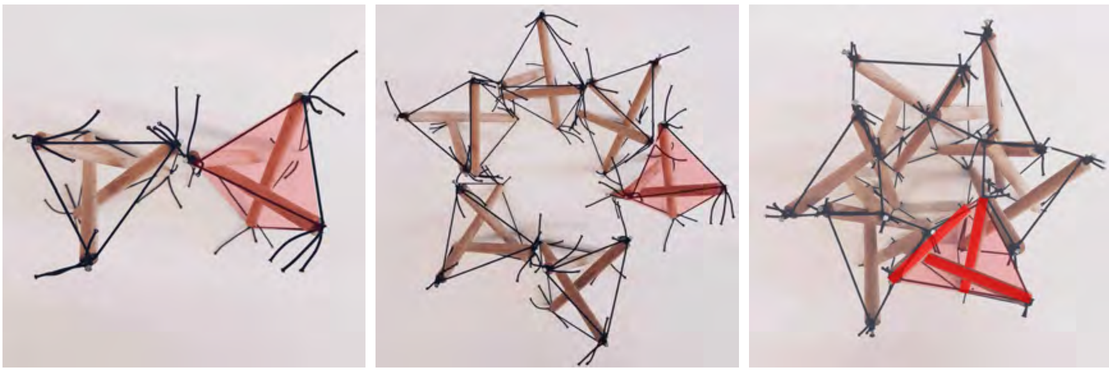

Figure 4.29: Triangular tensegrity modules to be assembled to one triaxial weave tensegrity module

of weave comprises both hexagonal and triangular elements. When mapping this to a tensegrity system, the binding includes six modules of three lattices on the outside and the hexagon module in the middle. As previously explained, when assembling tensegrity, the shared thread in the weave becomes a shared compression element. Therefore the hexagon module in the middle is not built up before assembly. The clockwise turned hexagon module is instead built up during the assembly from the compression element towards the middle in each triangular module, see figure 4.31.

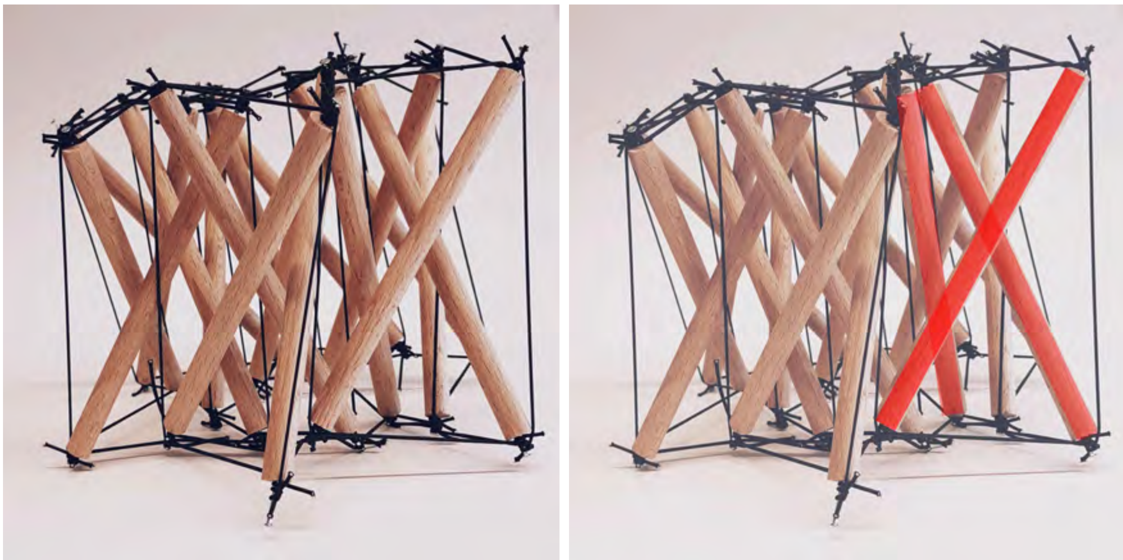

Figure 4.30: Triaxial weave binding as tensegrity module, side view

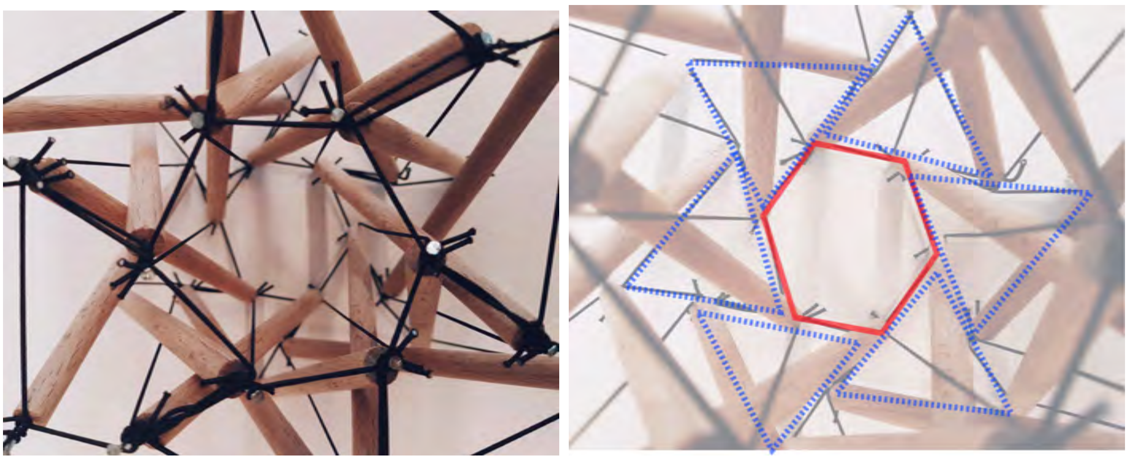

Figure 4.31: Zoom in on triaxial weave as tensegrity and basic shapes found in the module

4.6 Bobbin Lace Analysis

The same analysis method is used for the bobbin lace structures as was used for braiding and weaving. First a geometrical interpretation of the braiding pattern is done, figures 4.32 and 4.33. Here the line is added as geometrical visualisation of a twist of two threads. The bobbin laces analysed are ground laces, patterns which normally are made within this base lace have been ignored.

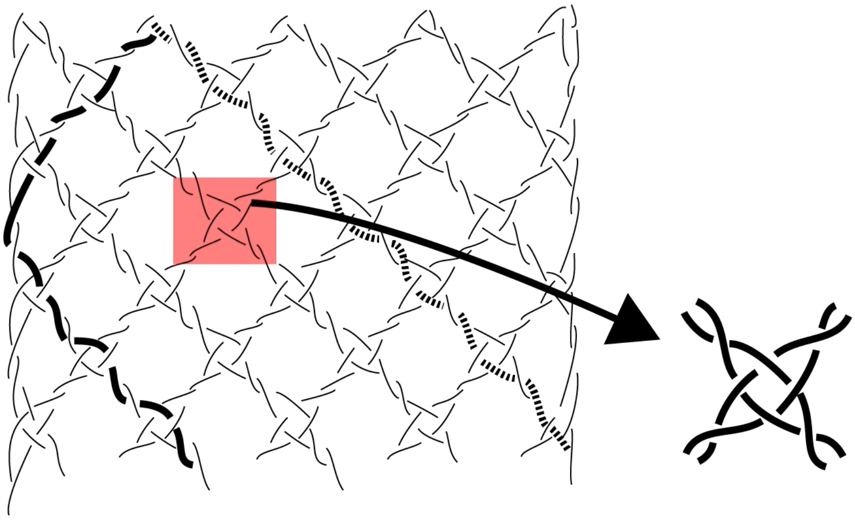

Figure 4.32: A hole ground bobbin lace with an isolated joint

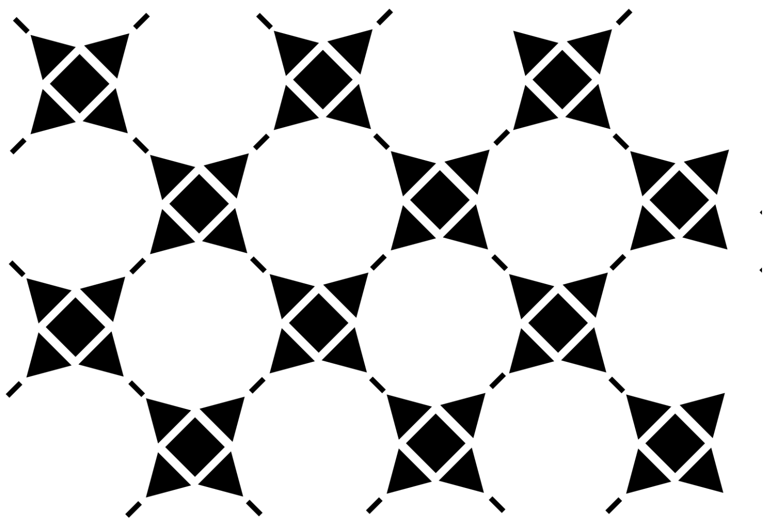

Figure 4.33: Geometric interpretation of a bobbin lace - the line connecting the modules is a geometrical visualisation of the twist between the bindings of the lace

Reciprocal structures and bobbin lace Since bobbin lace is a form of more advanced braiding, the same pattern of threads passing over and under is repeated. As explained in the previous sections, the polygons in the geometrical interpretations may be exchanged to reciprocal modules, figure 4.34.

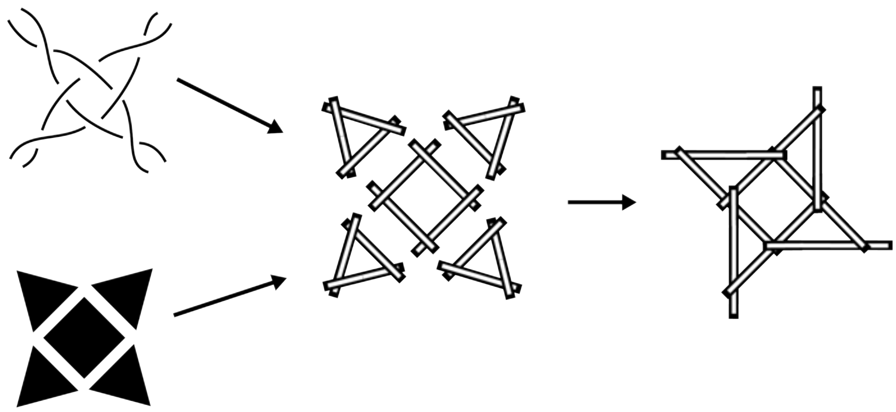

Figure 4.34: Joint translated to structure in reciprocal lace

The line representing the twist, on the other hand, can not possibly be replaced by a single twist module. In the model studies, this has been dealt with by using the same rod through the two neighbouring triangles, as a continues diagonal element, see figure 4.35

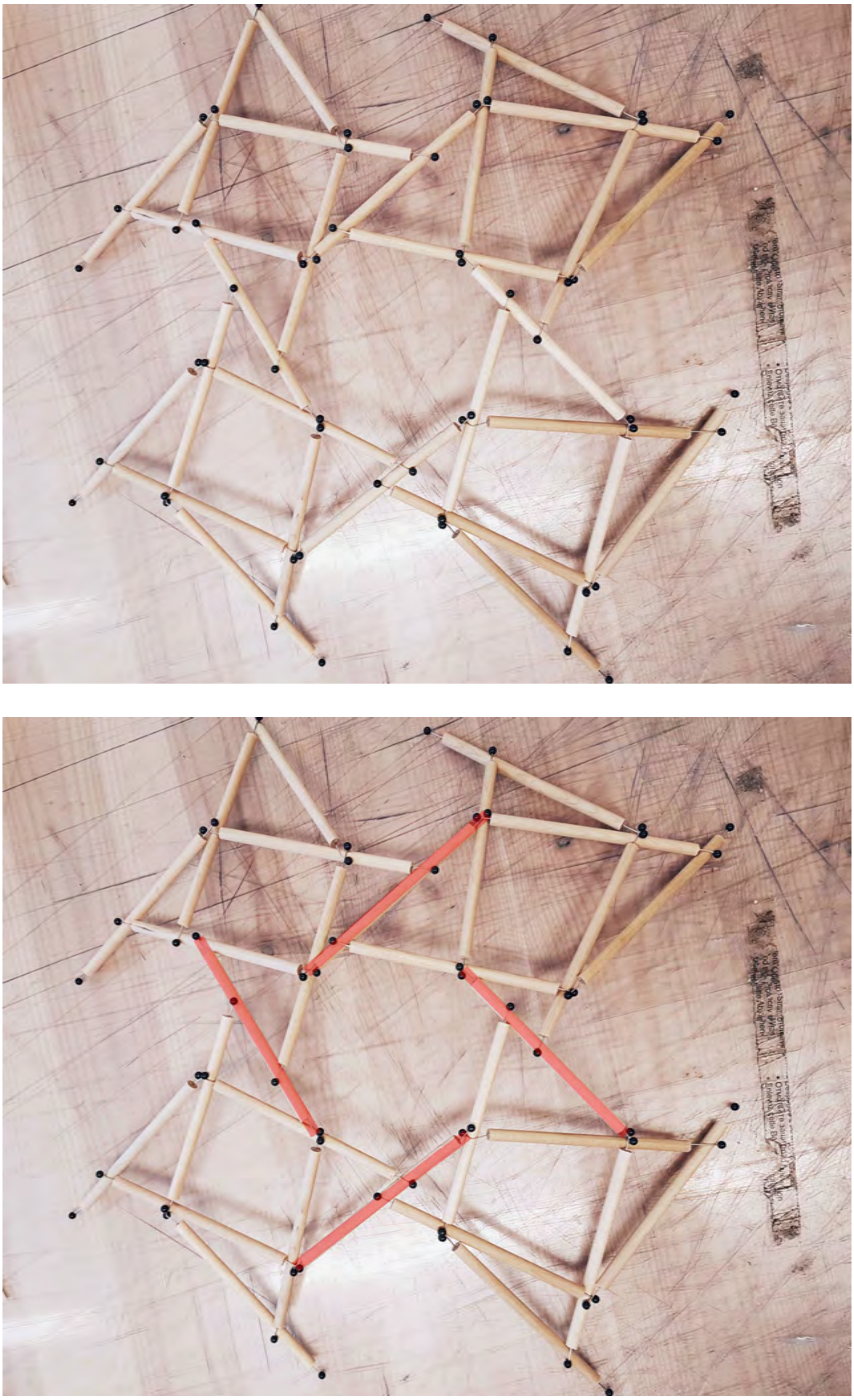

Figure 4.35: Reciprocal model of a bobbin lace with diagonal elements replacing the twisted yarns

4.7 Knit Analysis

Knitted structures with all loops in the same direction, cannot be built as a reciprocal structure. Even though some of the individual elements are subjected to both upwards and downwards forces the structure is not stable. In the reciprocal frame, previously described, each element is supported by the next by first going underneath one and over the next - resulting in three supports for each element, on alternating sides. In the attempt to make a mapping of a knit to a reciprocal structure this feature is not present. Hence, this does not work.

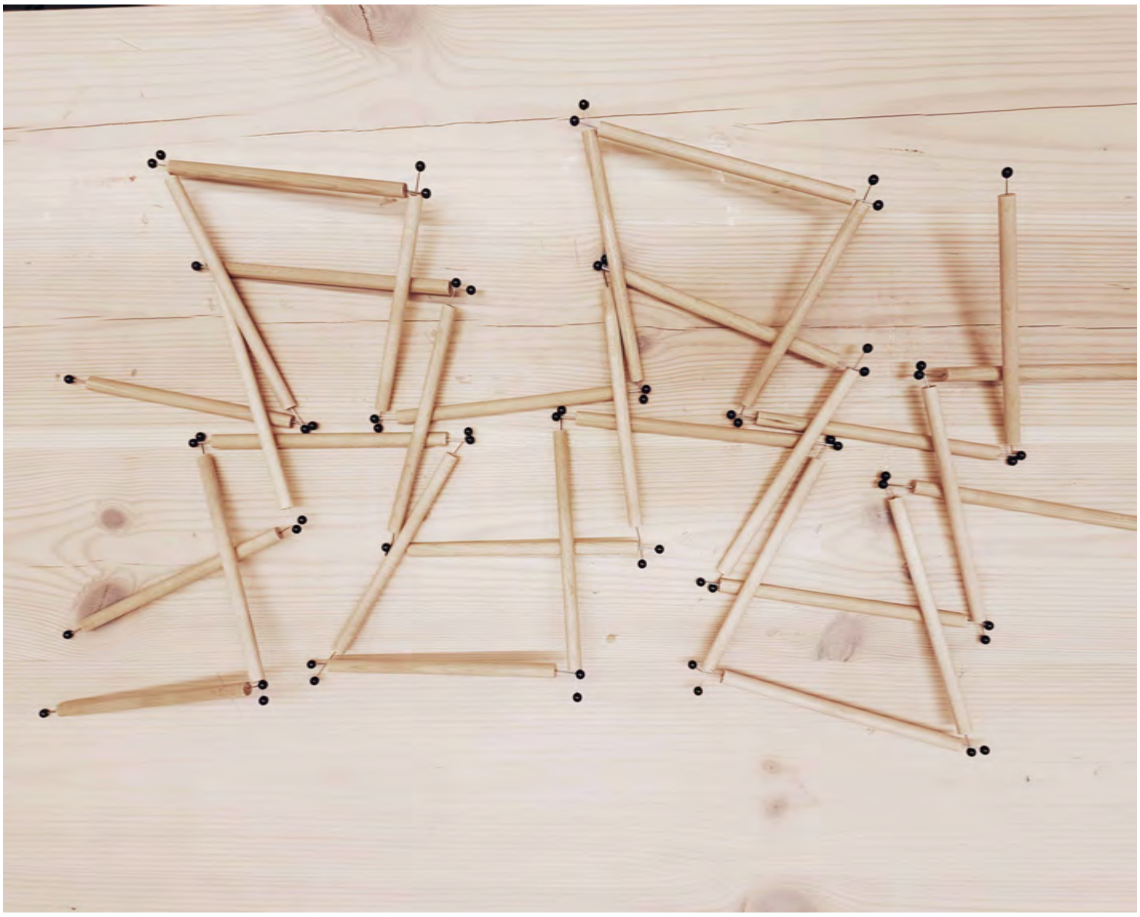

Figure 4.36: Attempt of a reciprocal model of a knit

4.8 General Conclusions

The general logic of a textile, where a material is built up by a repetition of joints, show much potential when translated into other kinds of structural systems. By assembling stronger "joints", possible to use in a larger building scale, an adaptable surface structure could be obtained. If the structure can "grow" in multiple directions through addition of more modules, a free-form structure adaptable to a general shape would be obtainable.

Most textile assembly methods analysed here are based on a biaxial or triaxial logic. This is key to make a flat surface structure. However, by combining geometrical shapes, more dome-like structures could be built. For example, a tensegrity structure could be made into a dome structure through a combination of squared and triangular shapes, i.e. modules of four and three rods. The scissor structures in particular show potential for a geometrically adaptable system. By tailoring the joints, these geometric connections could be designed to obtain a dome-like scissor structure. Using the dodecahedron-like base shape, a square viewing it from the top, the connections could be made to create triangular spaces between modules, thus resulting in a dome structure.

It is clear from this analysis that the logic of tensegrity and reciprocal structures share important features that are relevant in this type of mapping of textile logic. Even if they are different in terms of structural system categorisation, and thereby manner of load carrying, the geometrical properties show relevant similarities. The division of braids, weaves and laces into smaller cells is made relevant from the similarities between the zoomed-in-geometry of the threads and the stiff elements in reciprocal and tensegrity structures. Since a tensegrity module can be made from a reciprocal frame, the same mapping of textile to reciprocal structures may be used for tensegrity. Both types of modules are based on a circular logic where the structure in fact is a helix turned either clockwise or counterclockwise. Without this feature, the translation of a weave, with cells turned in reversed directions, would not be possible.

It has been shown in this reference analysis that woven structures and braids may be built up as both reciprocal and tensegrity structural systems. The bobbin lace, even though some adjustments are needed, at the twist for example, can also be mapped onto these kinds of structures.

As some examples show that tensegrity structures may be assembled vertically as well as horizontally, there may be potential to construct a structure with both an adaptable surface form as well as thickness. However, this has not been further explored in this thesis, and given the torsional behaviour of tensegrity structures it is not obvious how this type of layering would be obtained or how it would behave.

The correlation between platonic bodies and tensegrity systems, also show future potential for a three dimensional, adaptable structural system. Both in terms of its global form and the height of the structure. The truncated dodecahedron, assembled as a tensegrity structure, showed some similarities to a single unit of four compression elements. By analysing this further, the answer to how tensegrity might be assembled in multiple directions may be found.

However, the knitted structure, with much possibilities in its original form, showed little potential in the present analysis.

5

Concept Development

From the previous chapters it has become clear that there are many common features between textiles and the mentioned structural systems. To proceed, three concepts will be presented in this chapter. Each concept is based on an interpretation of a textile combined with a structural assembly method.

Each concept is derived in the meeting point between textile and structural mechanics. The three concepts that will be presented are:

- **Scissor structure - Platonic (Octahedron geometry)**
- **Tensegrity structure - Triaxial weave**
- **Reciprocal structure - Bobbin lace**

The simple tensegrity module of three rods is assembled into a triaxial weave, bobbin lace is braided by stiff elements resulting in a reciprocal structure and the platonic body - octahedron - is assembled as a scissor structure.

Each concept is compiled of single modules which, as in a textile, may be assembled in multiple directions in the 2D plane. Using digital analysis, the assembling of the concepts and evaluation of them will be carried out.

The aim of this thesis is to translate the logic of textiles into larger scale structures, to show that there is an area of use for these kinds of structures and to show whether or not these are feasible to build. Hence, detailed solutions of joints and final sizing of members are not included.

5.1 Software Tools

The digital models of the different concept have been developed digitally using the Rhinoceros interface and Grasshopper© in combination with the plugins Kangaroo© and Karamba©.

Grasshopper is a graphical algorithm editor, integrated in the Rhinoceros modelling program. With the Rhinoceros interface one can get instant feedback of the programming made in Grasshopper. The geometry of each structural concept is modelled using Grasshopper. The plugin *Kangaroo Physics* is a Live Physics engine where interactive simulations of the form-finding as well as optimisation and constraint solving process' can be produced. This is used to form-find the geometry of both the tensegrity and the reciprocal structures.

The FEM software Karamba, also a plug-in to Grasshopper, is used to evaluate the structural behaviour of each concept. It is a parametric structural engineering tool for accurate analysis of structures, e.g. spatial trusses, frames and shells.

5.2 Octahedron Scissor Structure

The first concept chosen to be developed further is the combination of scissor structures and platonic solids. By a textile-like assembly the resulting structure can "grow" in three directions as an array of modules. This results in a surface geometry with some resemblance to a woven structure, though there are connection joints rather than a braided connection.

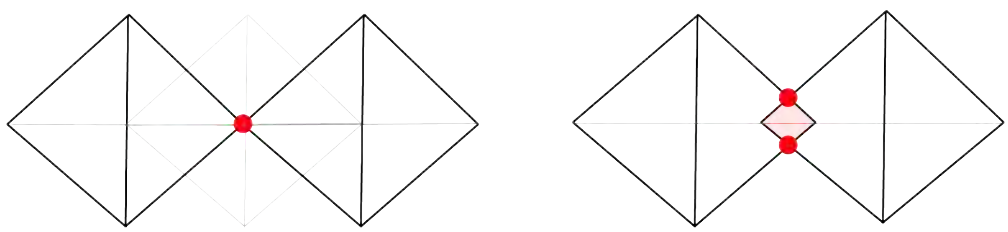

Figure 5.1: The connections between octahedron scissor modules; ArchInTex system (left) and octahedron scissor structure (right)

The concept of the octahedron scissor structure is based on the models made in the ArchInTex workshop, but further developed in terms of position of attachment points between elements. Where the modules from the workshop were attached by 3D joints at the ends, they are here attached closer to each other, by hinges on the rods, shown in figure 5.1. This results in a small diamond shape between all modules, seen in figure 5.2.

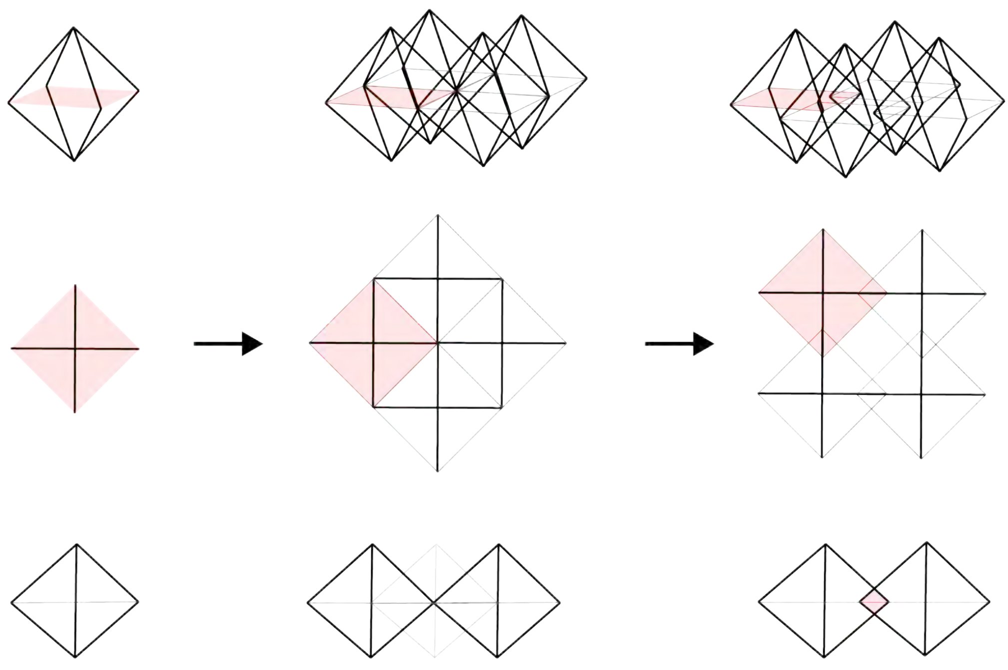

Figure 5.2: Single module into ArchInTex system and finally into adjusted concept

Possible Variations The concept of the octahedron scissor structure is planar and orthogonal. By changing the joints in the scissor module this geometry could be further developed into, for example, hexagonal structures, fig 5.3 and 5.4 (top view). Thereby these structures could be applied to other free form surfaces than the orthogonal. By combining different kinds of modules, e.g. squares and triangles or pentagons and hexagons, the assembled structure could also take a more dome-like form. Some variations of principle can be seen in figure 5.5

Figure 5.3: Concept for a variation of joints

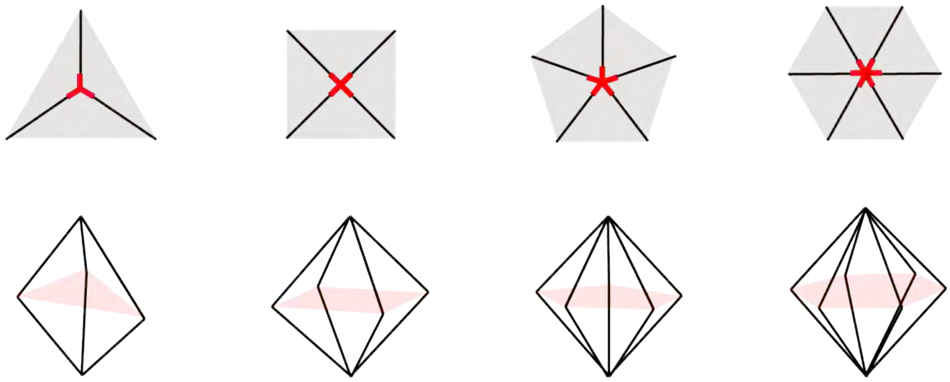

Figure 5.4: With the same logic, different geometrical forms can be made through the use of different joints

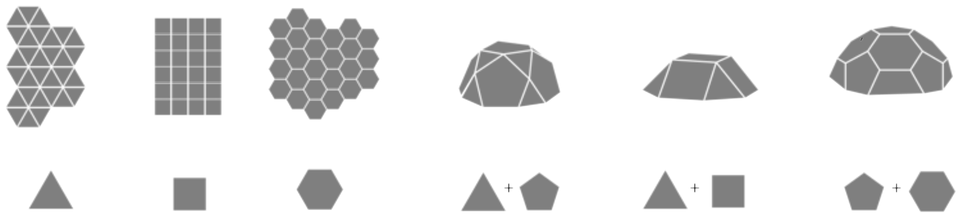

Figure 5.5: Examples of geometrical compositions for planar and curved surfaces

5.2.1 Digital Assembly of Octahedron scissor Structure

The scissor structure is modelled digitally using a grid as base for positioning the modules. Within the modules each beam is modelled by two lines, enabling the position of a hinge on the rod while still retaining the properties of a beam, see figure 5.6.

The hinges are modelled such that the resistance in the joint can be adjusted by assigning a rotational spring stiffness, in kNm/rad. The hinges themselves are modelled by very short lines between the beams to enable the possibility for a moment free hinge.

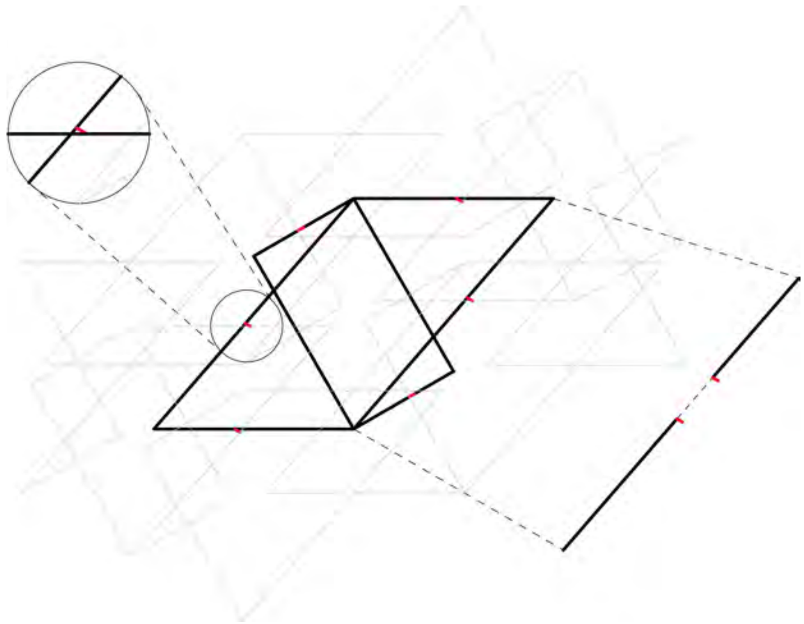

Figure 5.6: Modelling of scissor structure; each rod modelled in separate pieces, hinges in red

5.3 Tensegrity Triaxial Weave

The concept of the tensegrity weave is a direct continuation of the triaxial weave tensegrity model made, see figure 4.30. Being a direct mapping of the triaxial weave into a modular tensegrity system, the structure can expand in three directions in plan, similar to the model in figure 4.30. The triangular tensegrity modules are assembled such that the compressed element of one module is attached in between two compressed elements, at the middle of one tension band, on the next. This logic generates a geometric pattern of the weave where the triangles are slightly shifted in relation to each other, so that each corner meet at the midpoint on the neighbouring triangle's edge, see figure 5.7.

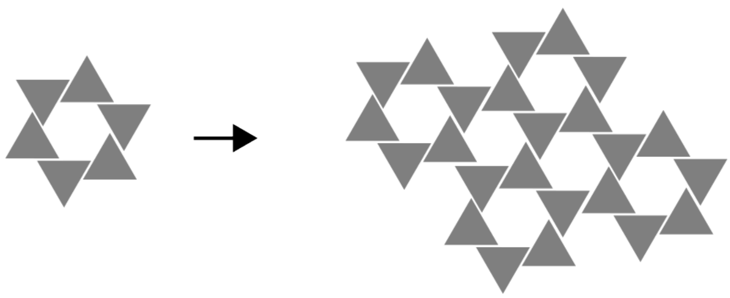

Figure 5.7: Geometric pattern of the tensegrity triaxial weave

5.3.1 Digital Assembly of a Triaxial Tensegrity Weave

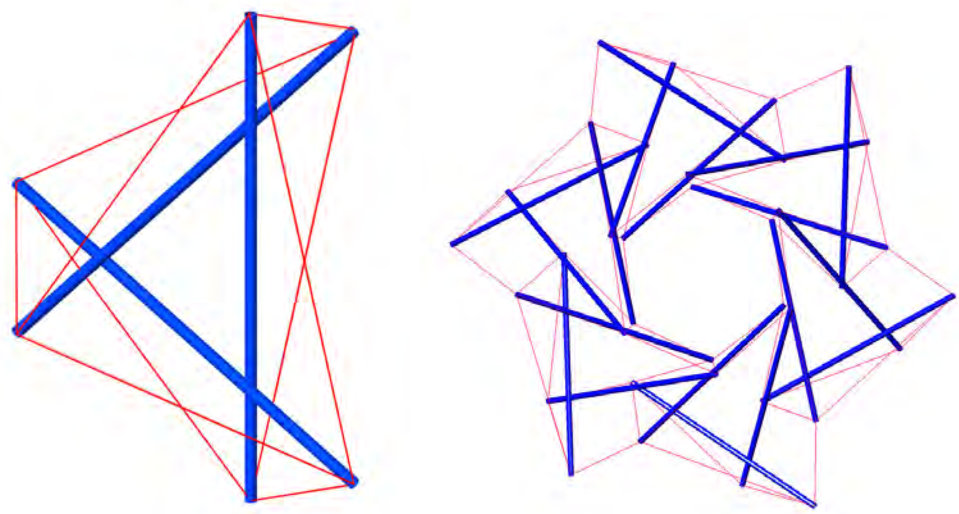

Figure 5.8: Digital tensegrity module into a tensegrity triaxial weave binding module

To assemble the tensegrity triaxial weave digitally "regular modules" are used. The regular modules are not in self-equilibrium but are modules where the bottom triangle is parallel to the top one, see left image in figure 5.8. These are copied along the geometric pattern of figure 5.7. Each "tension band" in the top and bottom triangles are modelled in two parts to enable the attachment of another compressed element at the midpoint of each cable.

After the regular modules are positioned over the desired surface form, kangaroo is used to form-find the structure, figure 5.10 and **??**. During this form-finding process each module twists, causing the entire structure to change form. If not attached to the ground, the assembled surface rises in certain parts and is only supported on the ground by some of the edge modules.

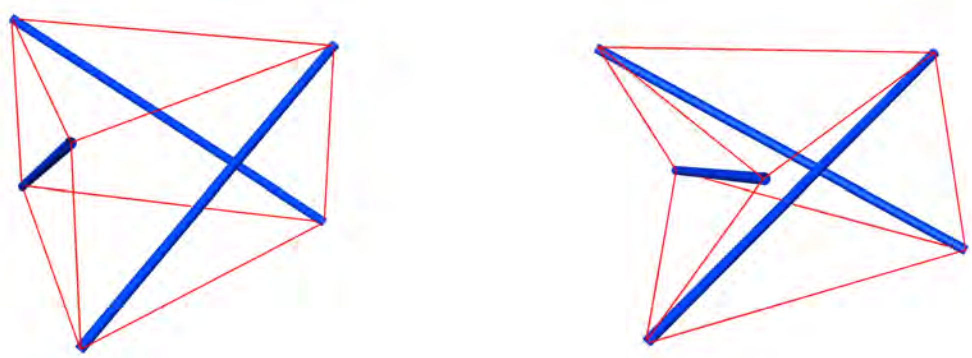

Figure 5.9: Form finding of a single module of three rods

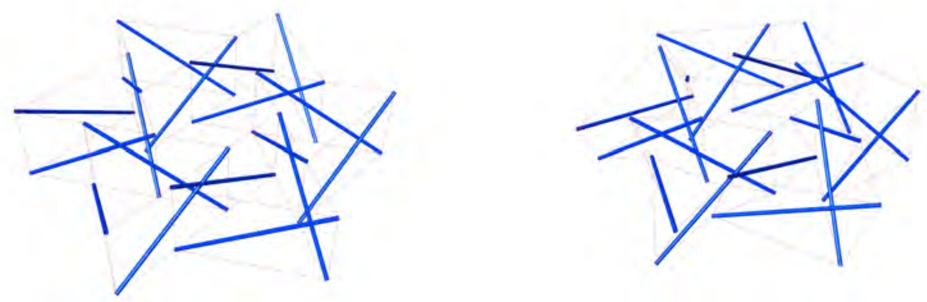

Figure 5.10: Form finding of a tensegrity weave module

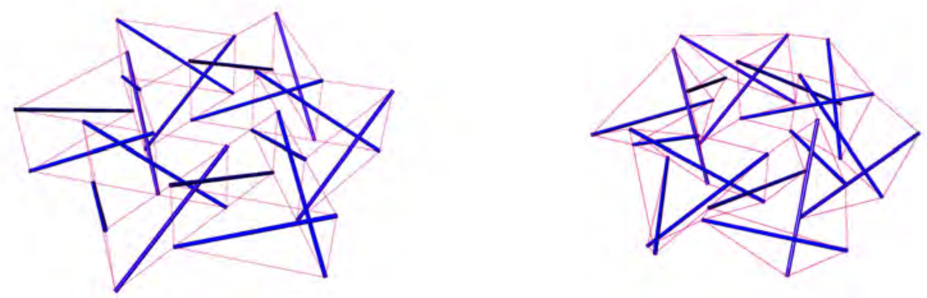

Figure 5.11: Form finding of a tensegrity weave module with shorter tension bands on the bottom side

5.4 Reciprocal Lace

The bobbin lace can, as has been explained in the previous chapter, be analysed in the same manner as a weave and a braid, and be mapped to a reciprocal structure. The difference being the twist of the yarn which in general is not used in either braiding or weaving. This twist cannot be directly translated into a reciprocal module due to it only comprising two elements. In the model studies made and presented in the Reference Analysis chapter, figure 4.35, this twist has been made by using one rod between the modules, on which the secondary two rods rest.

The concept of the a reciprocal lace build upon the plain hole ground lace pattern. And similarly to the model studies made in the Reference Analysis, this concept depend on a modular thinking. Each knot, or binding, in the lace is seen as one reciprocal module, stable on its own. The connection of these modules is made at the twist. The twist is in this concept development made as a continuous diagonal between the modules. On this diagonal, rods from both modules rest.

Figure 5.12: Modular reciprocal lace model

Figure 5.13: Physical model of four reciprocal lace bindings

5.4.1 Digital Assembly of a Reciprocal Lace

Geometrical model of a reciprocal lace The reciprocal lace is modelled as a modular structure. The base module is the basic reciprocal frame of four rods combined with four diagonals, see figure 5.12.

According to the previous model tests, figure 5.12, when assembling these base modules into a structure of more modules, some elements are superfluous. To obtain a reciprocal structure, one diagonal is continuous between two modules on which two rods, one from each module, rest. To model this digitally, each base module is designed with only three of the diagonal elements.

A reciprocal frame, in itself, obtains an arch-like curvature due to the geometry of straight elements resting on top of the next, explained in the Reference Study chapter. The height of a reciprocal structure is increased through increasing the number of elements used. The practical models of this structure show the same conclusion. Therefore, the four base modules are assembled into a higher structure where each base module is rotated upwards. However, in this step, the rotation angle need not be the correct one but the aim is rather to obtain the correct hierarchy in the geometry.

This model is then form founded with Kangaroo to obtain the final geometry. The

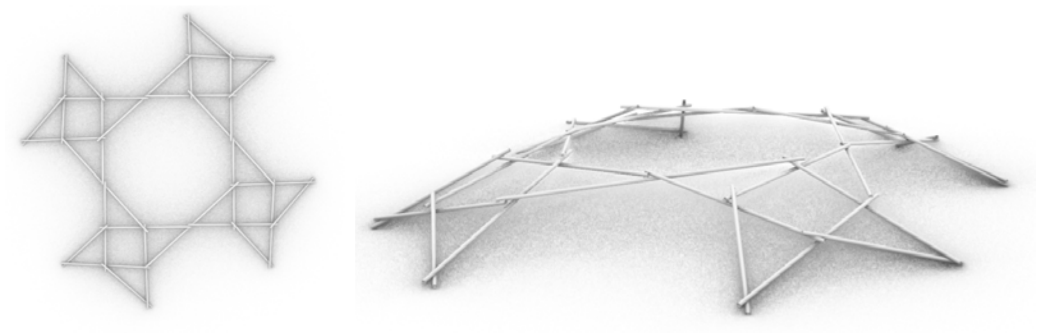

Figure 5.14: Digital modelling of the base geometry of a reciprocal lace

points where one element lays on the next are found where the least distance is between the elements. Here an eccentricity, a distance, is prescribed. The eccentricity prescribed, in combination with the position of the rods in the base model, yield the final geometric form. The form-finding made here is thus not based on an applied force and the eccentricity prescribed is based on the thickness of cross section of the elements.

6

Case Study

To test the potential of the three concepts, the digital models are applied to a free form roof structure; a continuous roof structure in the void between a number of buildings. Digital modelling enables an easier, or more time efficient, assembly of the modules. The different concepts are adapted geometrically to the surface in different, yet modular ways. The modules are then applied to a simplified model of a square part of the roof to evaluate their load carrying capacity.

6.1 Free Form Roof Structure

A replacement of the roof over the interior courtyards in Nordstan Gothenburg is to be evaluated. The irregular space between six building volumes, shown in figure 6.1, is to be covered by a continuous roof structure. The structure covers a surface of 11112 m^2 and spans between 10 m in the smaller areas up to 29 m in the larger. All buildings are assumed to be of the same height and thus the supports of the roof structure are in a common horizontal plane.

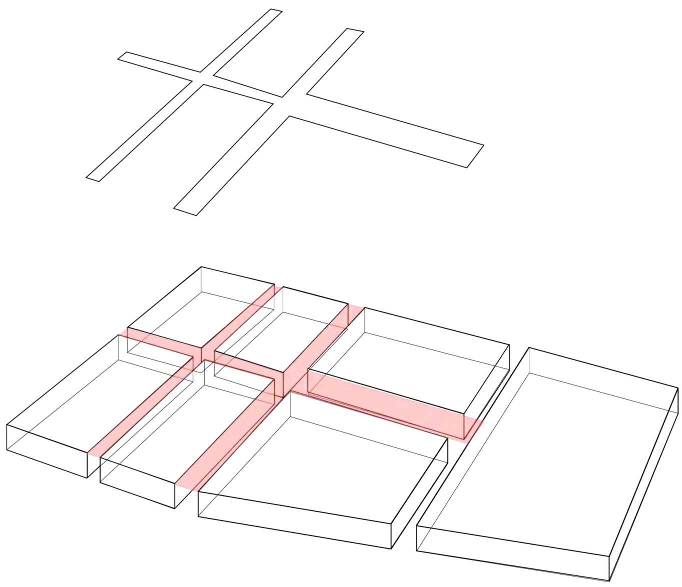

Figure 6.1: Irregular roof form between buildings in Nordstan Gothenburg

6.2 Geometric Application

Starting with a planar surface with irregular, yet orthogonal, edges, each concept - module - is assembled according to its own logic, see figure 6.2. The scissor structure is modelled along a regular square grid, which fits the starting surface. The tensegrity structure on the other hand, which is not orthogonal, is assembled along the weave pattern. The modules are placed out on the surface in the triaxial pattern, excluding the modules which are positioned outside of the surface. Thus, the array of modules along supporting edges is not completely parallel to the sides and some modules are placed on, and somewhat outside, of the supporting edge.

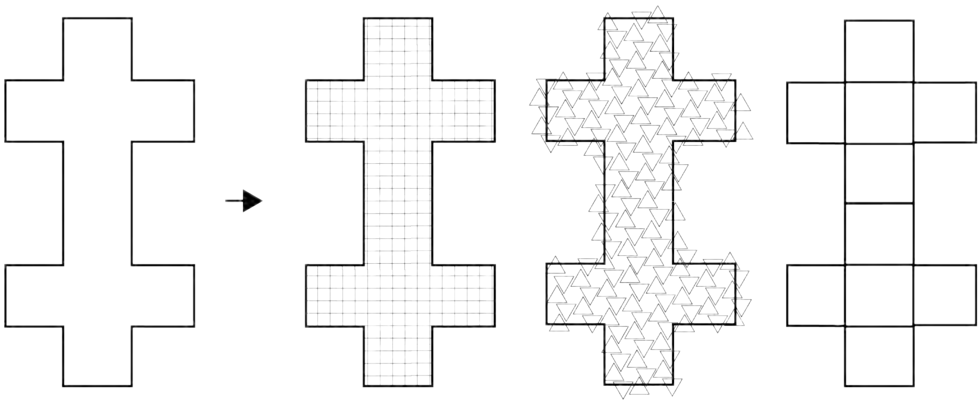

Figure 6.2: Geometrical application of the three different concept on the roof geometry: scissor structure is placed according to a grid; tensegrity modules are placed according to a pattern where modules outside of the surface are excluded; reciprocal lace, division of the surface is made into a few smaller squares where an edge beam is assumed.

When assembling the reciprocal lace it is evident that it "rises" in height for each module added. In both the physical and the digital models, this structure is build up so it can be supported by an outer square. If one would assemble this structure into a rectangular geometry, the supports on the long edge would have to be positioned higher (in a bow-like manner) than the supports on the short edge. The required geometry is both irregular and oblong. Since the reciprocal lace structure needs support along all outer edges, there are two methods for a geometric application of this structure. The first alternative is to work with the silhouette of the outer supporting walls, so that the structure can be supported at the required height. This would however require further analysis in terms of wall shape etc. The second alternative, which is used here, is to work with edge beams. The free-form surface is then divided into squares where each square edge is either a building wall or position of an edge beam, see figure 6.2. Within these squares the reciprocal lace structure may be built with all supports in the same plane.

The geometric application on the actual case roof surface of Nordstan is tested in one case, the scissor structure. By creating a continuous grid which is aligned to the

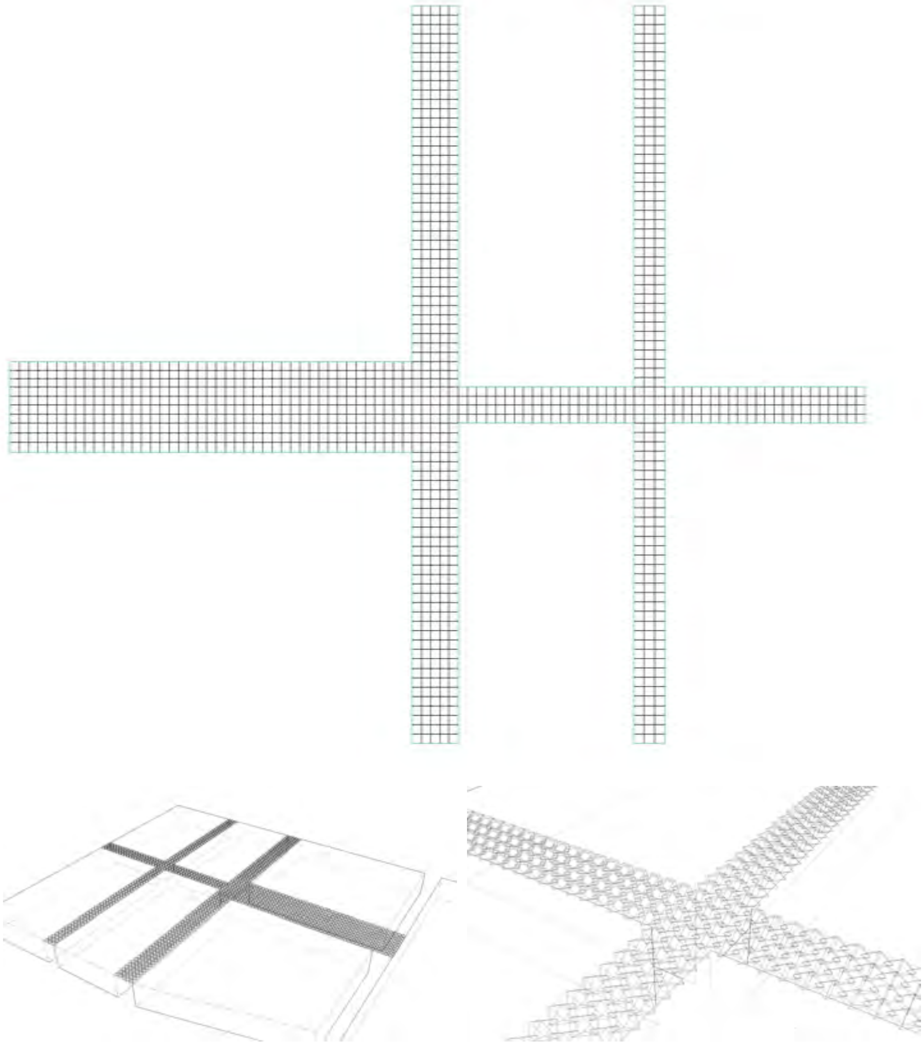

Figure 6.3: Grid adapted to the geometry of the roof surface in which the scissor structure can be placed (top) and scissor structure positioned along this grid

building edges with somewhat varying gap distances, the modular system is placed out over the entire roof structure, see figure 6.3.

6.3 Digital Application

To test the different concepts in terms of load carrying capacity a simplified model is used. Each concept is modelled digitally to cover a square with the side of 10 meters, a small piece of the larger roof geometry, see figure 6.4.

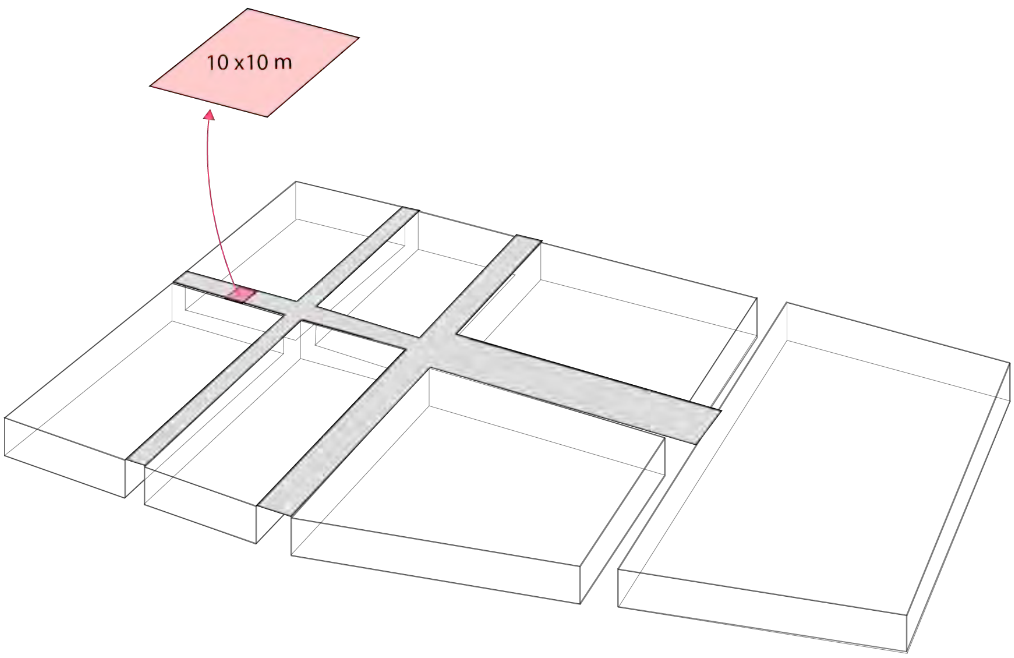

Figure 6.4: Simplified model for load testing

All concepts are assuming hinges at all sides of the square, giving support both vertically and horizontally. All concepts are modelled in timber, GL30c, with material properties according to Swedish Wood[28] and dimensions chosen from the available standard timber dimensions[29]. Each concept was tested with a range of dimensions in order to obtain the minimum possible amount of material to span the 10x10 m^2 area. Mutual for all concepts are that the elements they comprise of, are all relatively short in relation to the 10 m span - if for example comparing to a standard timber roof truss where at least one of the comprising elements has to span the full 10 m.

For all three cases, the structure is assumed to be loaded by a pvc coated polyester textile cover of 1.45 kg/m^2 [30] and a uniform snow load of 1.5 kN/m^2 (according to the snow zone for Gothenburg). Load combinations according to Eurocode has been used, 1.35 times the self weights and 1.5 times the snow load. Design strengths for timber has been calculated through:

$$\chi_d = k_{mod}\frac{\chi_k}{\gamma_m}$$

χ_d	design strength
χ_k	characteristic value of strength property
γ_m	partial factor for a material property
k_{mod}	modification factor taking into account the effect of the duration of load

$$\gamma_{m,C24} = 1.3$$
$$\gamma_{m,GL} = 1.25$$
$$k_{mod} = 0.8$$

according to Eurocode 5. [31]

The resulting sectional forces of the structures was obtained from the Karamba analysis; normal force, moment and shear force. From these the cross sectional stress' were calculated with:

$$\sigma_N = \frac{N}{A}$$

σ_N	axial stress
N	axial force
A	area of cross section

$$\sigma_{m,crit} = \frac{M_{y,crit}}{W_y} + \frac{N}{A}$$

$\sigma_{m,crit}$	critical bending stress
$M_{y,crit}$	critical bending moment
W_y	section modulus about strong axis y

$$\tau_d = \frac{3V_d}{2A}$$

τ_d	design shear stress
V_d	critical shear force
A	area of cross section

according to Navier's formula and Eurocode 5. [31]

Connections As described in section 5.2.1 the modelling environment of Karamba gives the possibility to specify the rotational stiffness of the connections of the structure. For a rigid connection a stiffness of 10000 kNm/rad was used, and for a hinged 0.001 kNm/rad. However, in reality the stiffness of the connections would be somewhat semi-rigid. In the master thesis *Connections in Timber Reciprocal Frames* carried out by Joel Gustafsson real life experiments were carried out on reciprocal timber connections in order to attain a more realistic value of the rotational stiffness, to be used in digital calculations. 3.5 kNm/rad was found by Gustafsson to be a fitting value for the actual rotational stiffness of the connections in reciprocal frames and thus used as value for the semi rigid connections in the analysis' of this thesis. [32]

Similar real life experiments should be carried out on the actual rotational stiffness one would be able to attain in a scissor system, when tightening up all connections between the rods. As this thesis was not meant to go in to this level of detail, the same semi-rigid rotational stiffness as for the reciprocal frame, 3.5 kNm/rad, was used for the scissor system as well. While most likely not being fully accurate, an inclination as to what the accurate results might be could be obtained from comparing the results from the rigid, semi-rigid and fully hinged models. Furthermore, it is sufficient for the purpose of this thesis; to compare between the systems.

6.3.1 Model Verification

To verify the digital model - the material properties, dimensions and connections etc. - a comparison was made between a standard roof truss from the Timber Guide by Swedish Wood[33] and the same roof truss modelled in Grasshopper and evaluated with Karamba.

The roof truss from the Timber Guide is made with timber of grade C24, with dimensions of the bottom-, mid- and top rods being 45x195 mm, 45x145 mm and 45x220 mm respectively, for a span of 11 m (including supports lengths). The trusses are assumed to be placed with a distance of 1.2 m, carrying a roof structure of 0.6 kN/m^2 and a snow load of 1.5 kN/m^2. The design capacities are obtained according to Eurocode 5, assuming safety class 2, climate class 2 and medium term load duration class.

The roof truss from *Swedish Wood* is designed to have a maximum deflection of 20 mm. With the deflection obtained from the Karamba analysis being 19.2mm the digital model is assumed to be accurate. The dimensions used and the resulting utilisation from the Karamba analysis can be seen in table 6.1 and the deformed structure in figure 6.5.

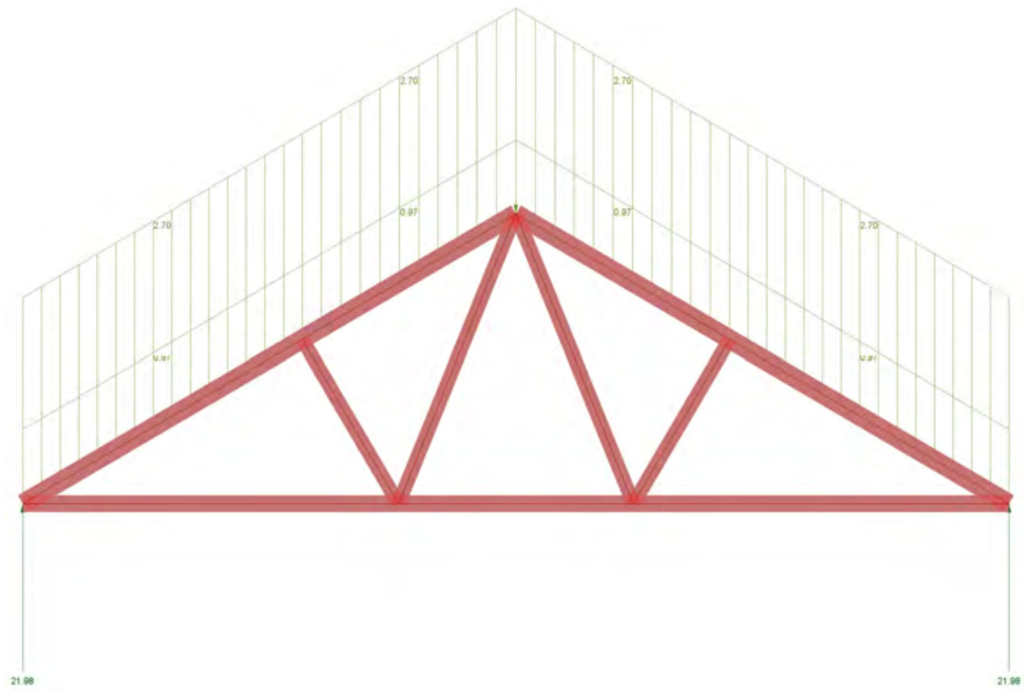

Figure 6.5: Standard roof truss from *Swedish Wood* analysed with Karamba

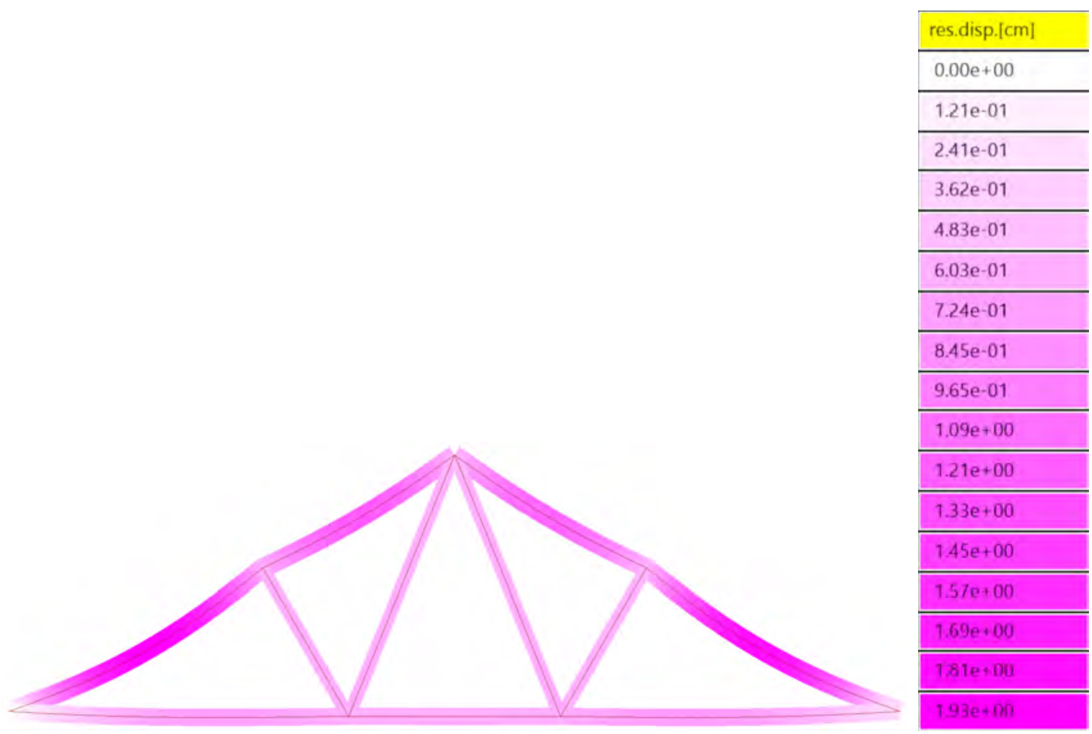

Figure 6.6: Displacement of roof truss analysed with Karamba, the deformation is scaled x10 in the figure

	Top rod	Mid rod	Bottom rod	
Section width	45	45	45	mm
Section height	220	145	195	mm
Utilisation:				
Tension		17	41	%
Compression	31	12		%
Bending	TBC	TBC	TBC	%
Shear	40	3	3	%

Table 6.1: Input and results of standard roof truss from *Swedish Wood* analysed with Karamba

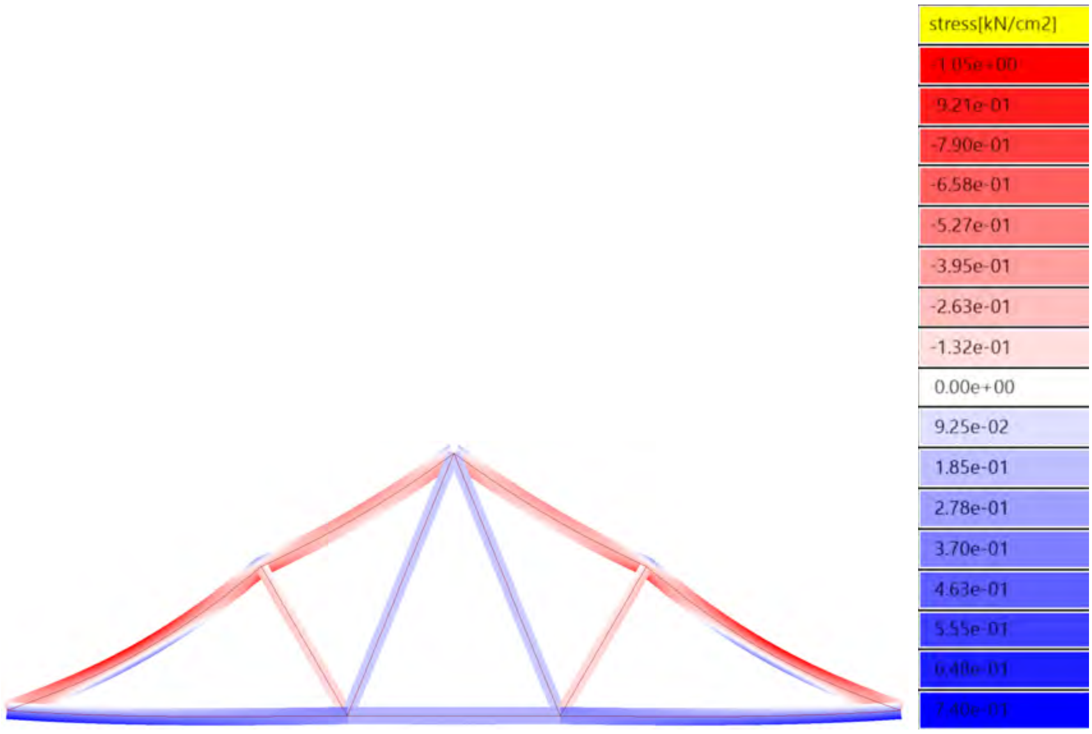

Figure 6.7: Axial stress distribution of roof truss analysed with Karamba, the deformation is scaled x10 in the figure

6.3.2 Octahedron Scissor textile roof

For the platonic scissor concept a few variations of the module configuration was tested, see the end of this sub chapter. The 10x10m^2 structure was modelled using the simplest of these - with symmetric modules around the xy-plane, two supports for each module along the edges and modules of length 3.75 m and width 1.88 m (element lengths were 2.1 m and 1.3 m) which was recognised as an appropriate size to span the 10m roof. The loads were assumed to be placed on the top nodes of the structure, at the meetings between the comprising scissor modules, see figure 6.9.

The platonic scissor roof structure was tested with a range of cross sectional dimensions in order to obtain the smallest possible amount of material use for the 10x10 m^2 span. Standard cross sectional dimensions were used, with 56x270 mm determined as the optimal one. As can be seen in table 6.2 this resulted in a structure of 4.4 ton. The digital model with rigid connections resulted in a deflection of 39 mm and the semi rigid of 128 mm.[1] The model with hinged connections buckled under the given load. Bending was the design stress for both the rigid and semi rigid models. However these are relatively low in both cases - *most likely due to the rather large skips between available cross sectional dimensions.*

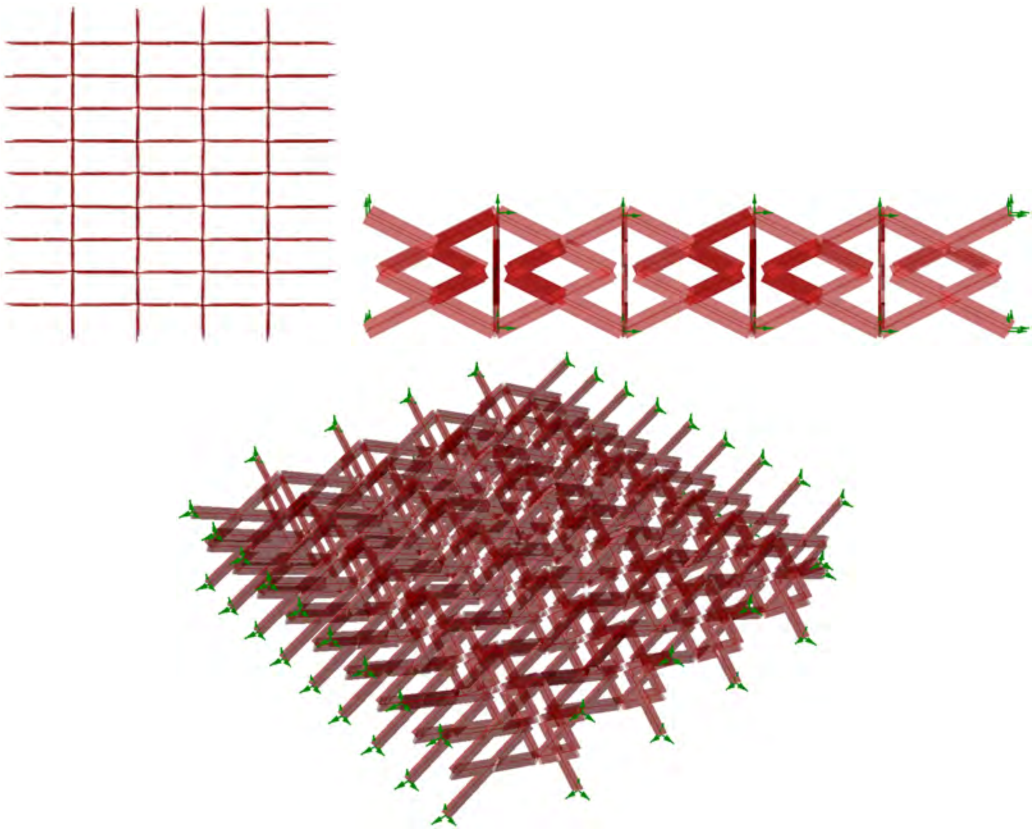

Figure 6.8: Input geometry for Karamba analysis of platonic scissor structure

[1] See section 5.2.1 and 6.3 for further explanation of the assumptions regarding rigid versus semi rigid behaviour

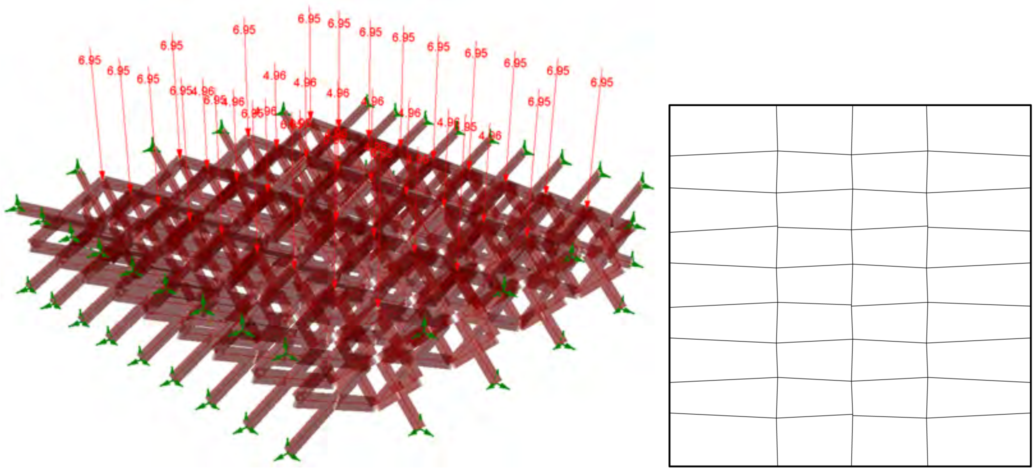

Figure 6.9: Loads applied to the digital model (left) - from textile roof cover and snow load - and its distribution (right)

MATERIAL	**56x270**	**56x270**	**56x270**	mm
CONNECTIONS	**Rigid**	**Semirigid**	**Hinged**	
TOTAL MASS	4.4	4.4	4.4	ton
DEFLECTION	39	128	Buckles	mm
Utilisation:				
Tension	8	9	-	%
Compression	8	8	-	%
Bending	56	67	-	%
Shear	32	37	-	%

Table 6.2: Results from analysis of platonic scissor structure performed with Karamba

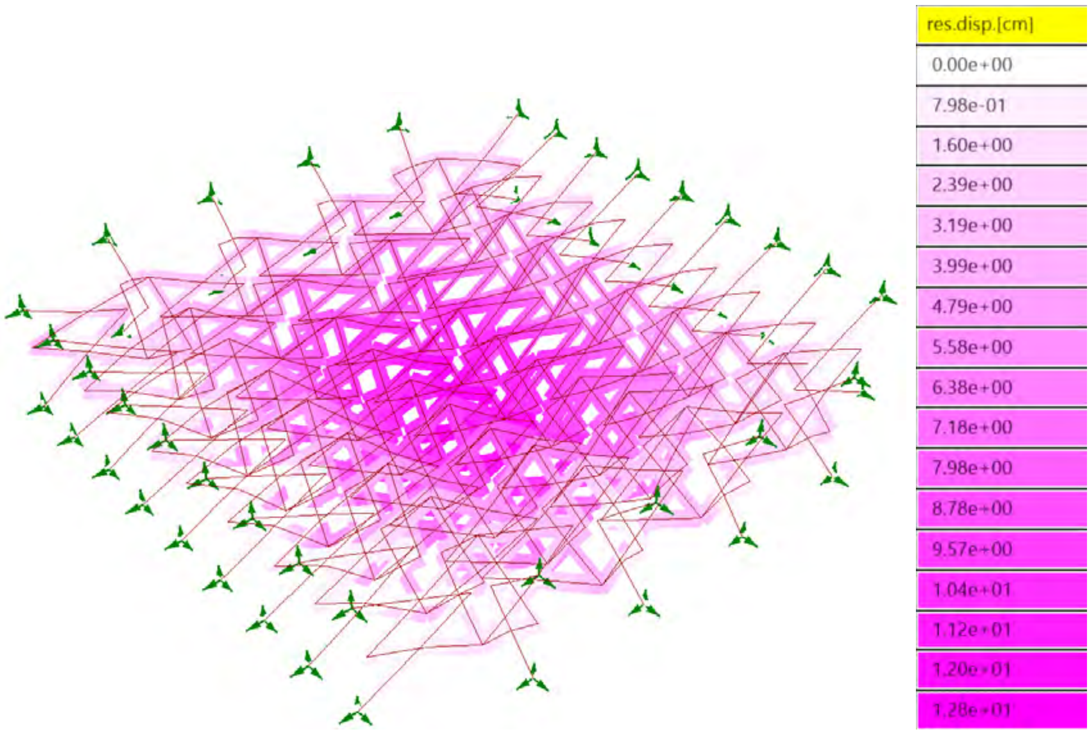

Figure 6.10: Deformed digital model of the platonic scissor structure, with semi-rigid connections, maximum deflection: 128mm

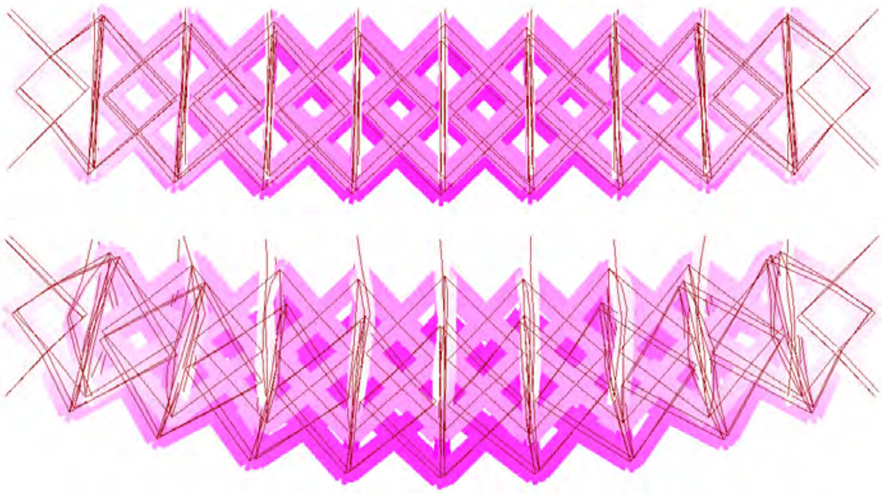

Figure 6.11: Deflection of platonic scissor structure with rigid (upper) and semi-rigid (lower) connections, maximum deflection: 39mm and 128mm respectively

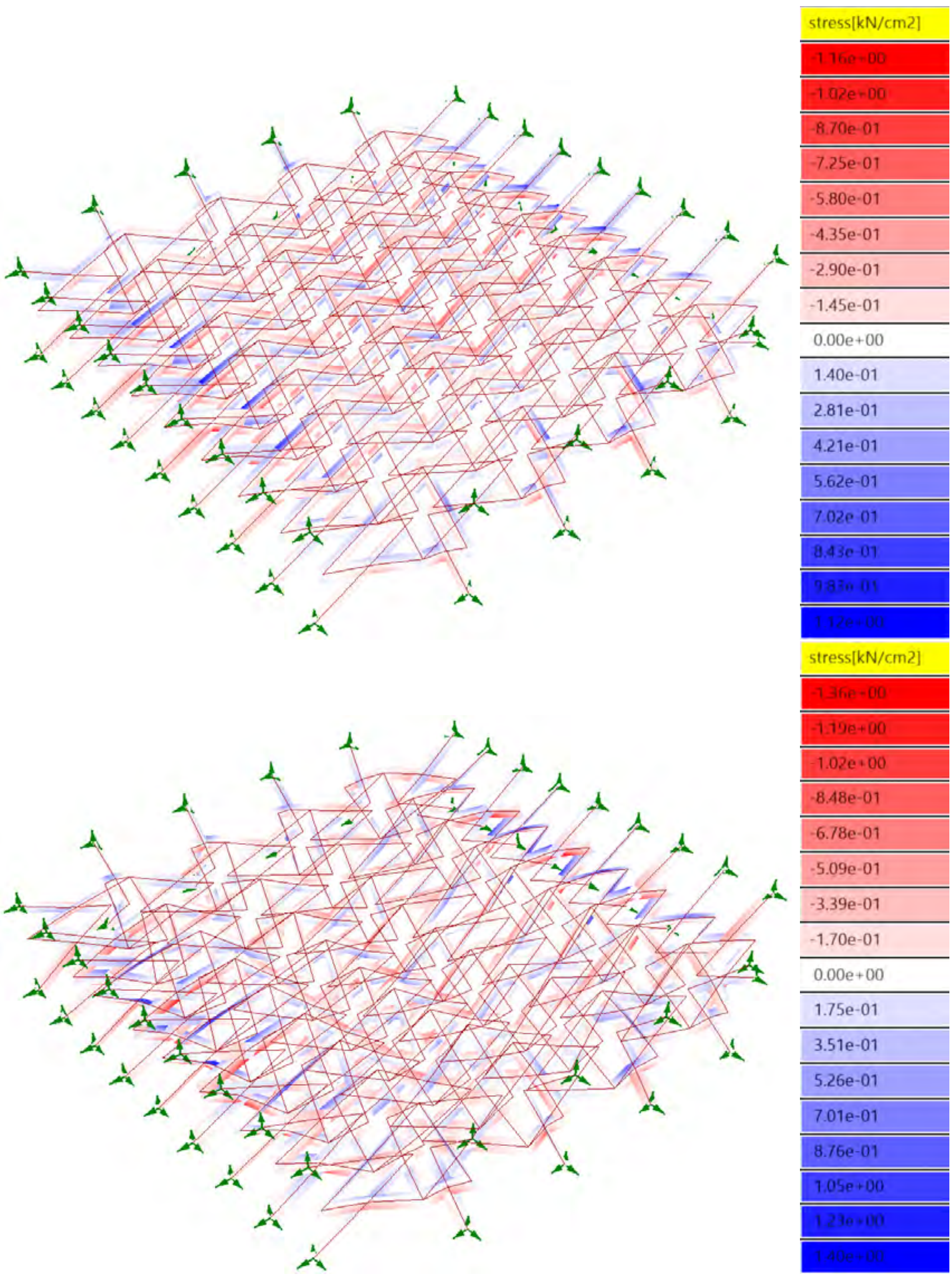

Figure 6.12: Axial stress distribution of platonic scissor structure with rigid (upper) and semirigid (lower) connections

Variations The global geometry of the scissor structures can be adjusted by alterations within each module. For example by adjusting the length relationship between the top and bottom rods, as well as the position of the hinges along these, an arch form can be obtained. Dimensional tests of a flat scissor structure compared to an arched one show that the load bearing capacity is increased in the arched geometry, see figures 6.13 and 6.19.

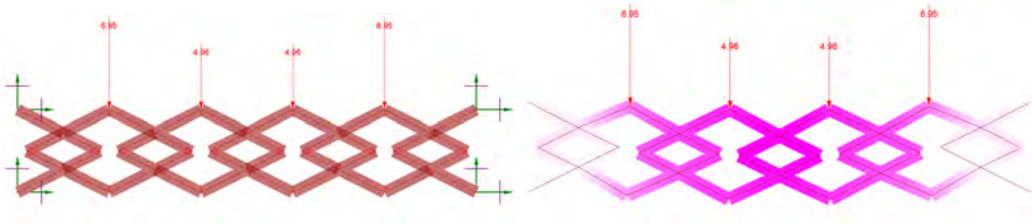

Figure 6.13: Symmetric modules in a straight line with two supports on each side and a module size of 3.75x1.88 m, *rigid* connections throughout. Undeformed (left) and deformed (right)

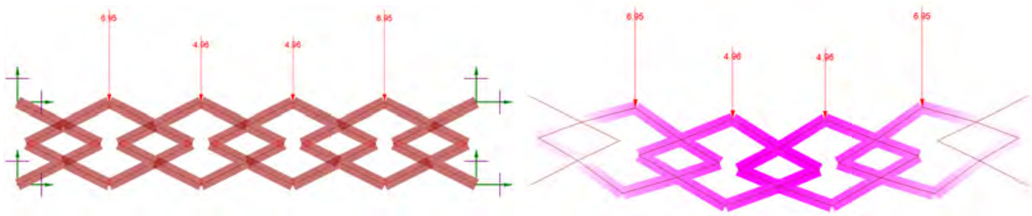

Figure 6.14: Symmetric modules in a straight line with two supports on each side and a module size of 3.75x1.88 m, *semi rigid* connections throughout. Undeformed (left) and deformed (right)

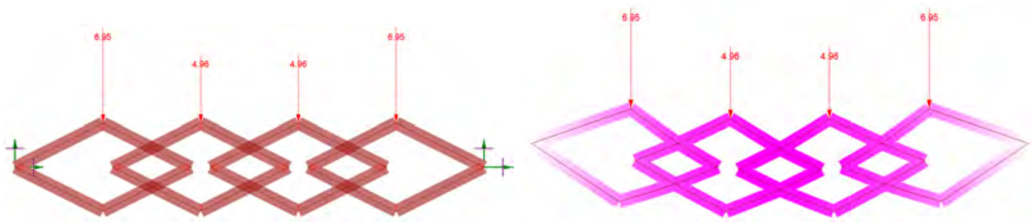

Figure 6.15: Symmetric modules in a straight line with *one* support on each side and a module size of 3.75x1.88 m, *rigid* connections throughout. Undeformed (left) and deformed (right)

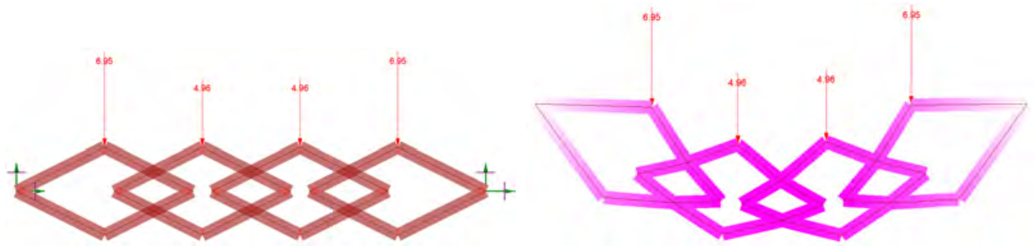

Figure 6.16: Symmetric modules in a straight line with *one* support on each side and a module size of 3.75x1.88, *semi rigid* connections throughout. Undeformed (left) and deformed (right)

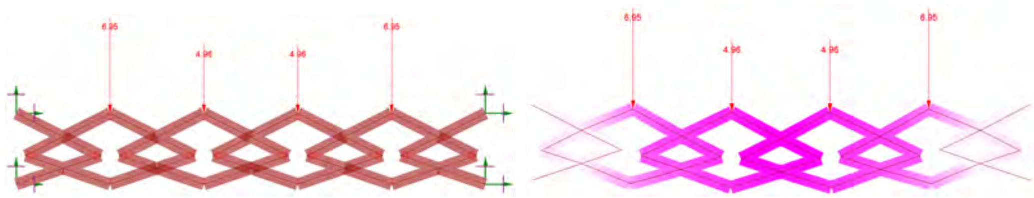

Figure 6.17: *Asymmetric* modules in a straight line with two supports on each side and a module length of 3.75 m and height of 1.4 m, *rigid* connections throughout. Undeformed (left) and deformed (right)

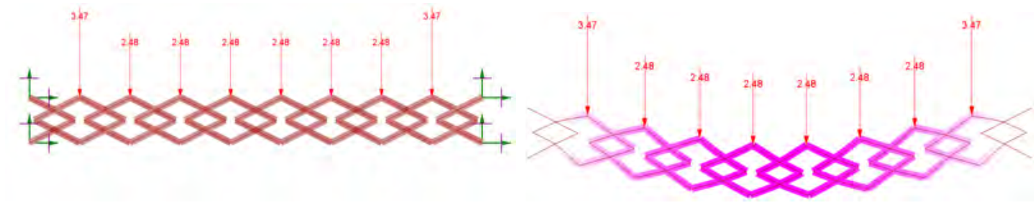

Figure 6.18: Symmetric modules in a straight line with two supports on each side and a *module size of 1.85x0.94 m*, *rigid* connections throughout. Undeformed (left) and deformed (right)

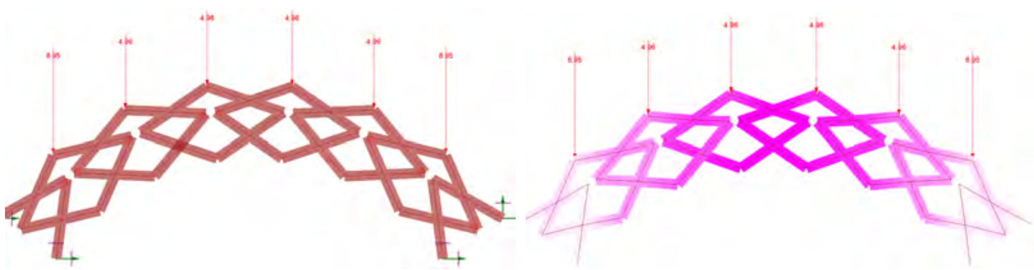

Figure 6.19: Symmetric modules in an *arched* line with two supports on each side and a module size of 3.75x1.88 m, rigid connections throughout. Undeformed (left) and deformed (right)

GEOMETRY	**Straight, large modules**				**Shorter bottom**	**Small modules**	**Arched**
SUPPORTS	**4 supports**		**2 support**	**2 support**			
CONNECTIONS	**Rigid**	**Semirigid**		**Semirigid**			
MASS TOTAL	311 kg	311 kg	247 kg	247 kg	302 kg	107 kg	412 kg
DEFLECTION	38 mm	121 mm	106 mm	409 mm	38 mm	150 mm	256 mm
UTILISATION							
Tension	7%	7%	7%	11%	8%	38%	1%
Compression	8%	9%	9%	10%	9%	37%	6%
Bending	50%	53%	88%	88%	52%	296%	33%
Shear	29%	33%	38%	54%	29%	147%	25%

Figure 6.20: Results from analysis of variations to platonic scissor structure performed with Karamba

6.3.3 Tensegrity Triaxial Weave

The tensegrity weave structure was modelled using bars of identical length (2.6 m) and cables of two lengths, one (shorter, 1 m) for the top and bottom triangles and one (longer, 2 m) for the connections between the top and bottom. A scenario with shorter cables for the bottom triangles, in relation to the top triangles, was tested during the Kangaroo form finding step of the process. As can be seen in figure 6.21 this resulted in a slightly more arched roof shape.

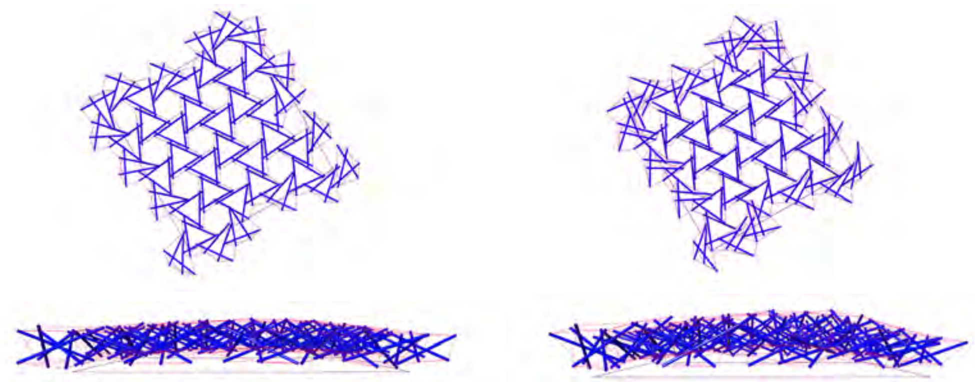

Figure 6.21: Influence of cable length during Kangaroo form finding - same length top and bottom (left), shorter length bottom (right)

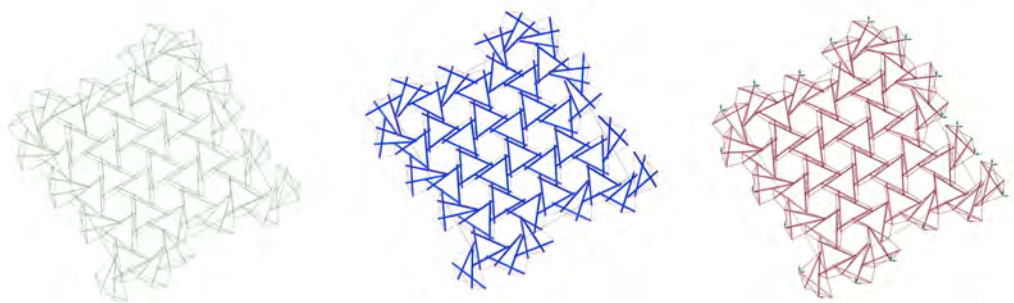

Figure 6.22: From 3D connectivity diagram to analysed structure (undeformed)

The supports for the model were placed where the modules reach outside of $10x10m^2$ square - as the grid of the structure is not orthogonal, this means an asymmetric/uneven distribution. The loads were assumed to be placed on the top nodes of each bar in the structure which, similarly to the supports, resulted in an uneven distribution. All connections throughout the structure are hinged in the model.

The tensegrity weave roof structure was tested with a range of cross sectional dimensions in order to obtain the smallest possible amount of material use for the $10x10m^2$ span. Standard cross sectional dimensions were used for the bars, with 75x75mm determined as the optimal one. For the cables, a diameter of 30mm was concluded to be sufficient, with a pre tensioning of 0.9 mm/m. As can be seen in table 6.3 this resulted in a structure of 4.1 ton with a deflection of 119mm. As per

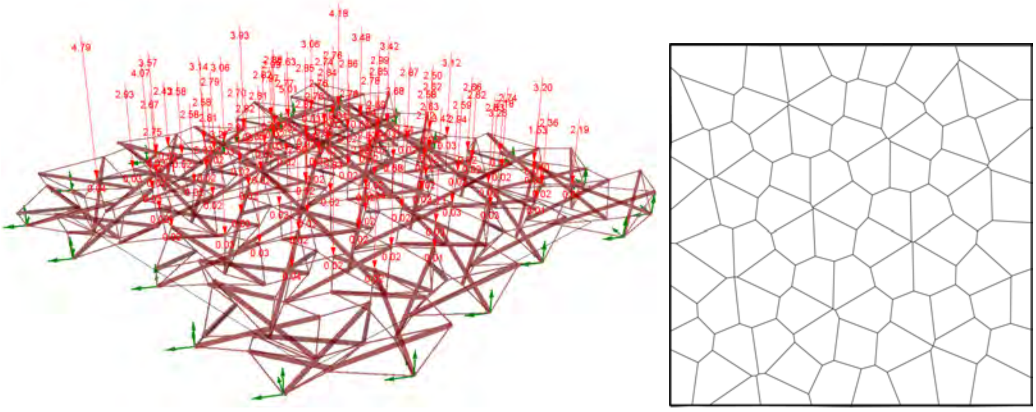

Figure 6.23: Loads applied to the digital model (left) - from textile roof cover and snow load - and its distribution (right)

the definition of tensegrity, no two of the bars in structure touch at any point. This yields a rather elastic structure, a possible explanation for the relatively large deflection of the model. With the chosen cross sectional dimensions the tension stress is governing, however still quite small as is the compressive stress. A possible reason could be the big jumps between available cross sectional dimensions for the bars, and the elastic behaviour of the structure with large deformations throughout.

BARS	**75x75**	mm
CABLES	**30**	mm
TOTAL MASS	4.1	ton
DEFLECTION	119	mm
Utilisation:		
Tension	54	%
Compression	32	%

Table 6.3: Results from analysis of tensegrity weave structure performed with Karamba

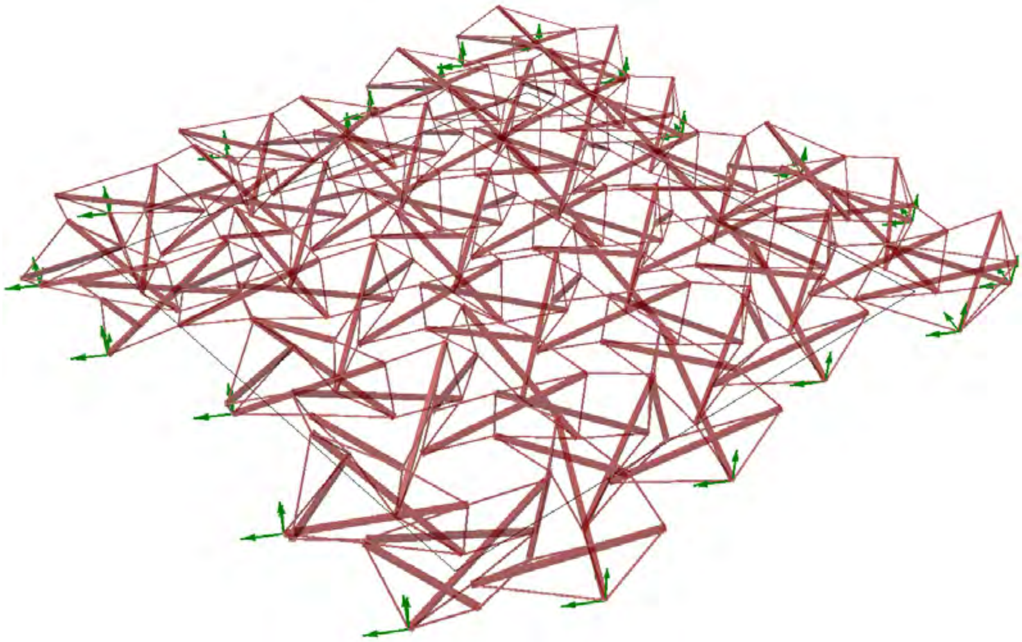

Figure 6.24: Undeformed digital model of tensegrity weave structure from Karamba analysis

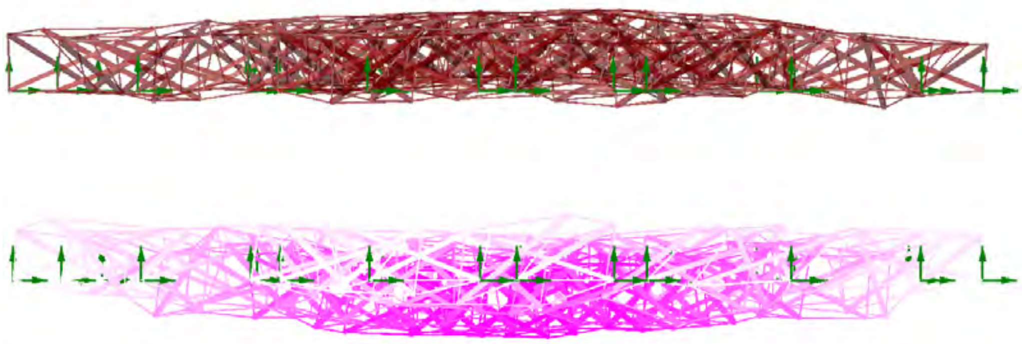

Figure 6.25: Undeformed (upper) and deformed model (lower) of tensegrity weave structure from Karamba analysis

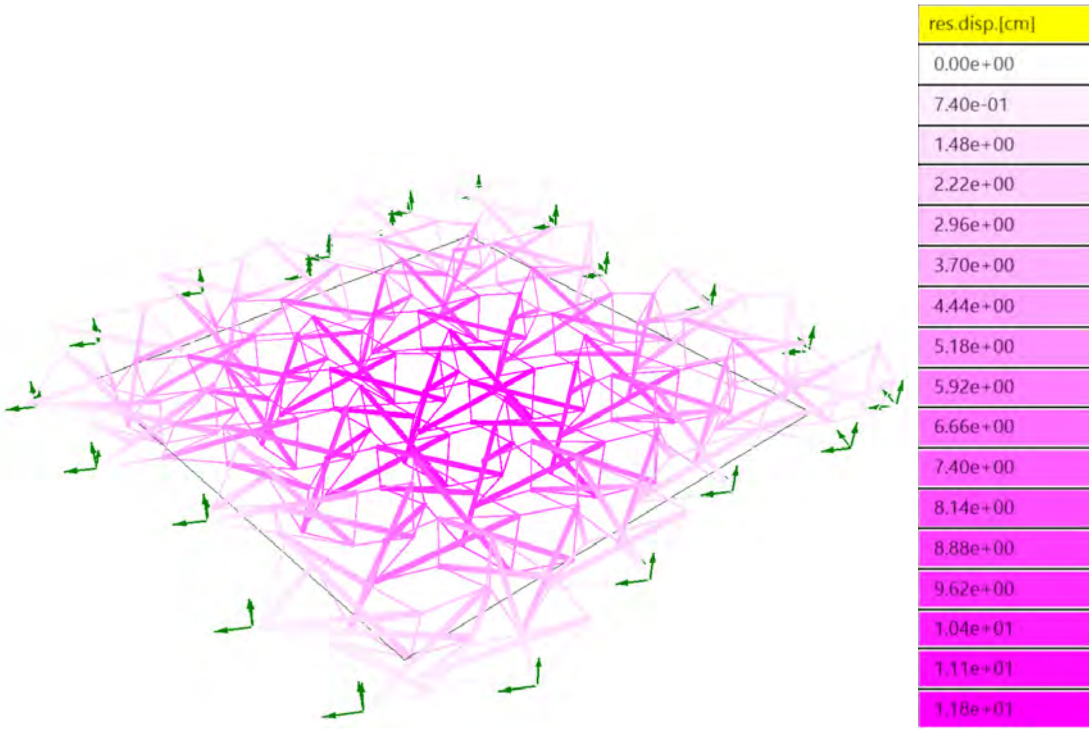

Figure 6.26: Deformed model of tensegrity weave structure from Karamba analysis

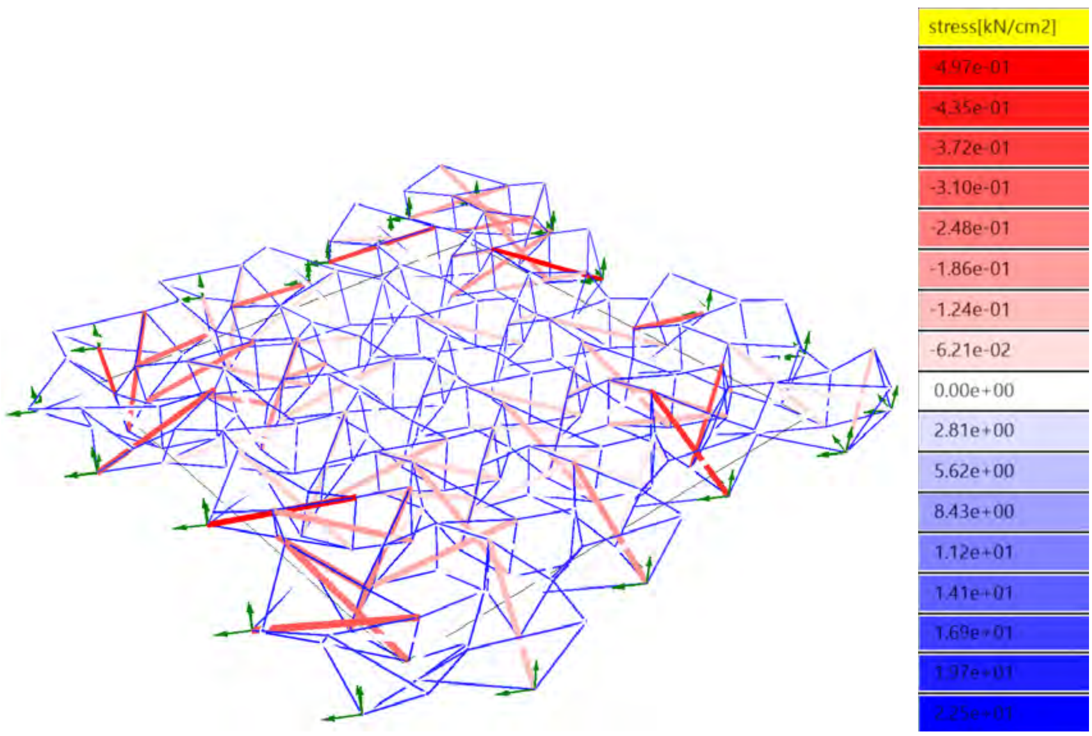

Figure 6.27: Axial stress distribution of tensegrity weave structure, analysed with Karamba. Compression in red, tension in blue.

Variations Similar to the Platonic Scissor Structure, the geometry of a tensegrity can also be adjusted with both local adjustments, and combinations of different modules.

The global geometry of the tensegrity weave can be altered by controlling the length of the tension bands in the modules. By using shorter tension bands in the lower side of the modules in an assembled system, the global geometry will take a more dome-like shape.

Using this principle on separate modules, one can also change the geometry locally in a structure. With further analysis one should therefore be able to build free-form surfaces with varying curvature as well.

That the basic tensegrity modules can be build based on polygon forms has already been discussed. Therefore the same principle of combining different polygon shapes to create a curved surface, as described for the scissor structures in figure 5.5 could be used to control the curvature of a tensegrity surface as well.

6.3.4 Reciprocal Lace Roof

The reciprocal lace structure was modelled using beams of three lengths - two (shorter, 2.7 and 3.6 m) for the base module and one (longer, 5.0 m) for the diagonals between the modules. Each of the four modules are identical but positioned/rotated individually in the 3D space. This yields a rather orthogonal grid, with possibilities for two supports per module, positioned symmetrically around the edge of the 10x10m^2 area. The loads where assumed to be placed on the top node of each beam in the structure, as can be seen in figure 6.29.

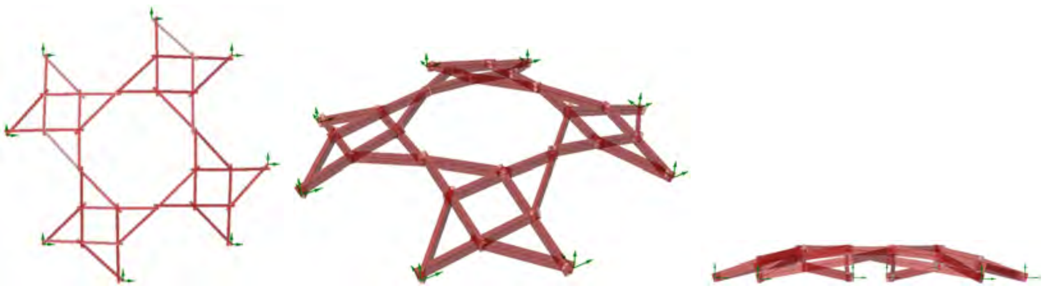

Figure 6.28: Undeformed digital model of reciprocal lace structure from Karamba analysis

The reciprocal lace structure was tested with a range of cross sectional dimensions on order to obtain the smallest possible amount of material use for the 10x10m^2 span. Standard cross sectional dimensions were used, with 190x270mm determined as the optimal one. As can be seen in table 6.4 this resulted in a structure of 2.1 ton. The analysis of the case with rigid connections throughout gave a deflection of 15mm and with semi rigid connections 130mm.[2] The design stress turned out

[2]See section 5.2.1 and 6.3 for further explanation of the assumptions regarding rigid versus semi rigid behaviour

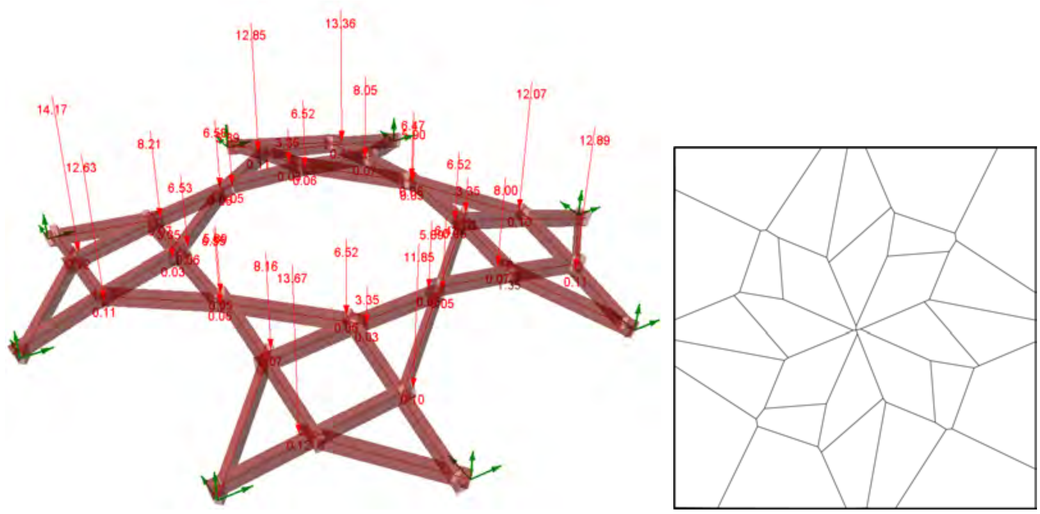

Figure 6.29: Loads applied to the digital model (left) - from textile roof cover and snow load - and its distribution (right)

to be shear stress, most likely a vital/big reason for this is the relatively low shear strength of glulam beams (4 MPa) .

MATERIAL	**140x315**	**140x315**	mm
CONNECTIONS	**Rigid**	**Semirigid**	
TOTAL MASS	2.1	2.1	ton
DEFLECTION	15	130	mm
Utilisation:			
Tension	0	0	%
Compression	18	15	%
Bending	43	58	%
Shear	100	87	%

Table 6.4: Results from analysis of reciprocal lace structure performed with Karamba

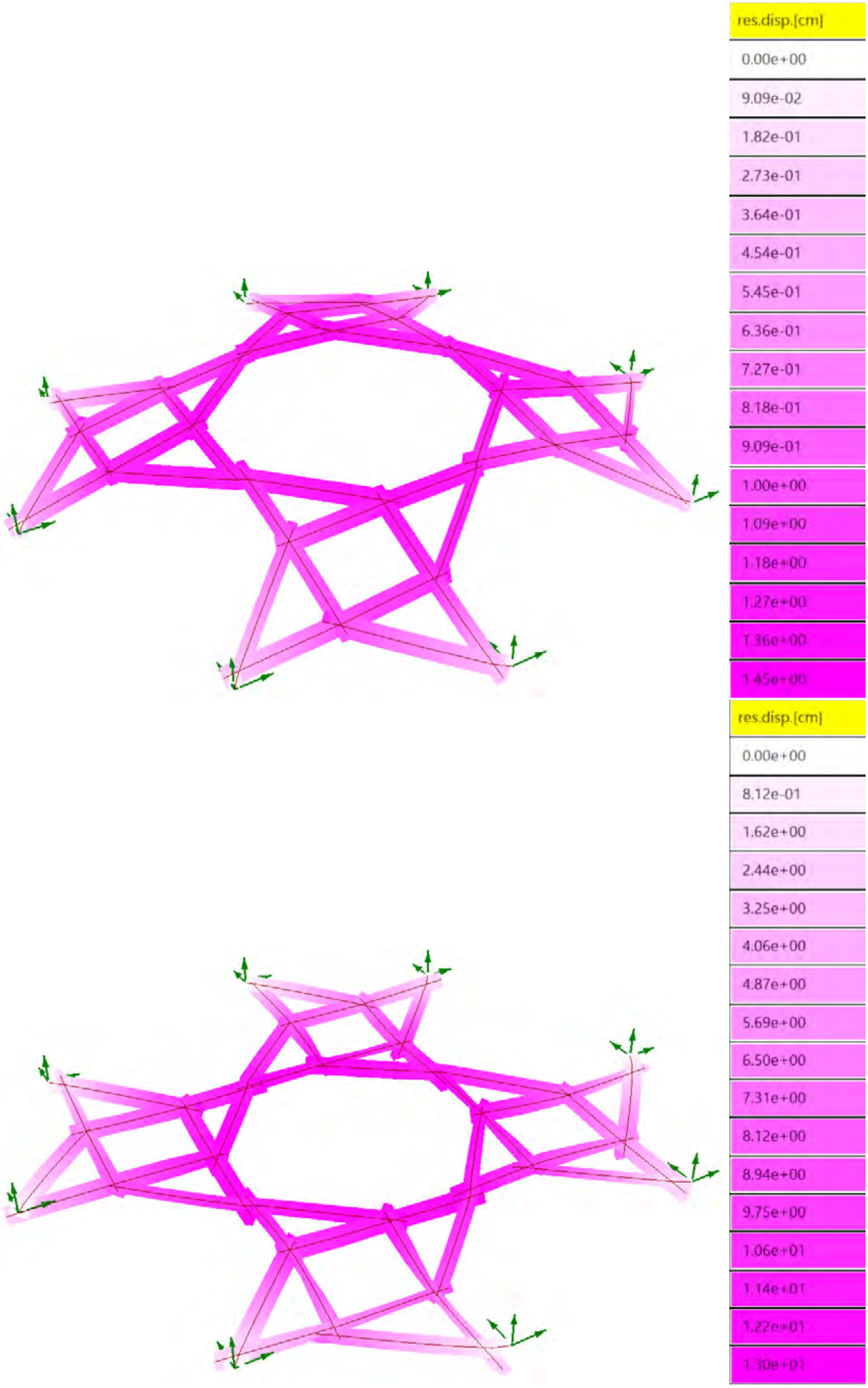

Figure 6.30: Deformed model of reciprocal lace structure from Karamba analysis, rigid connections (left) and semi-rigid connections (right)

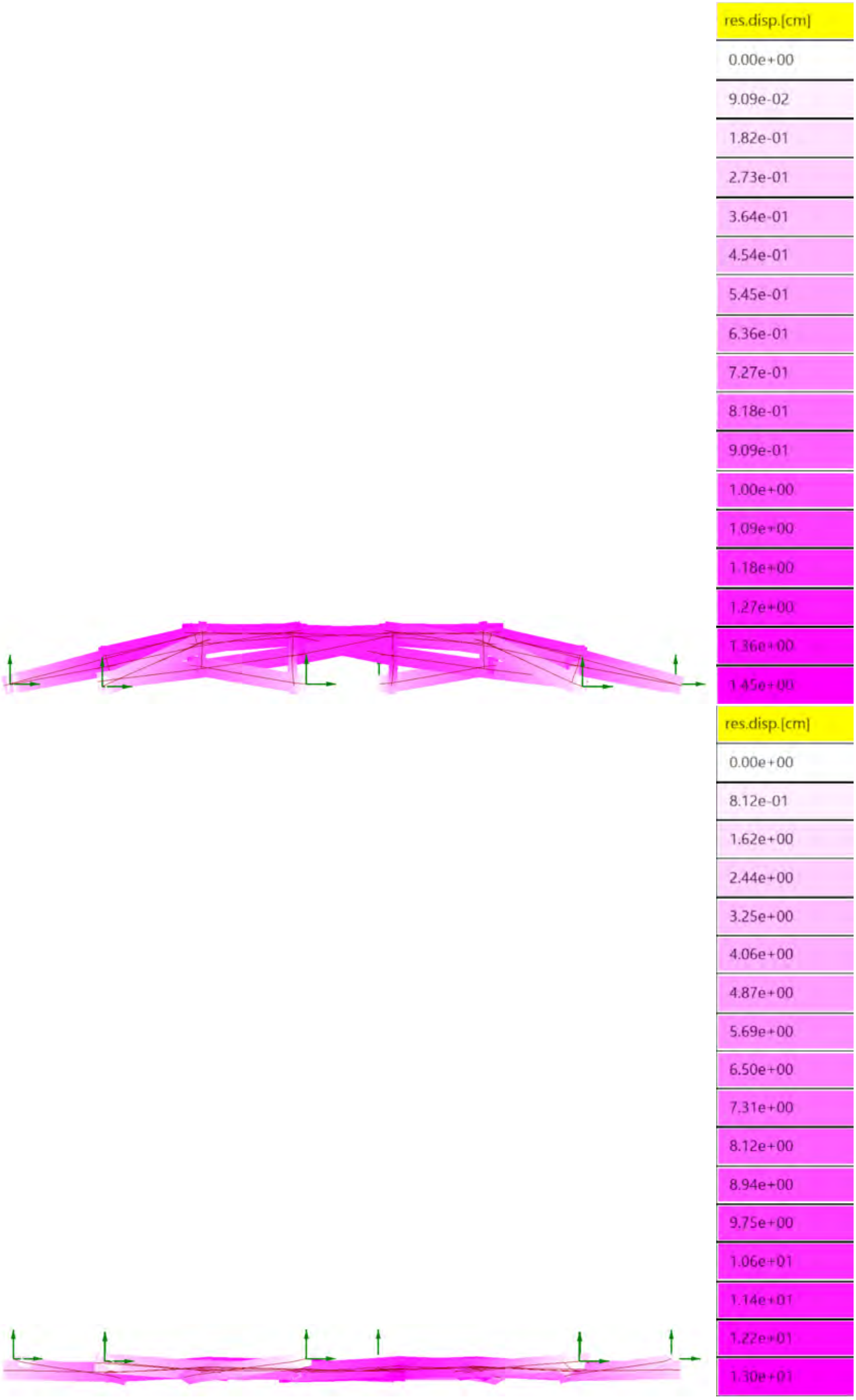

Figure 6.31: Deformed model of reciprocal lace structure from Karamba analysis, rigid connections (left) and semi-rigid connections (right)

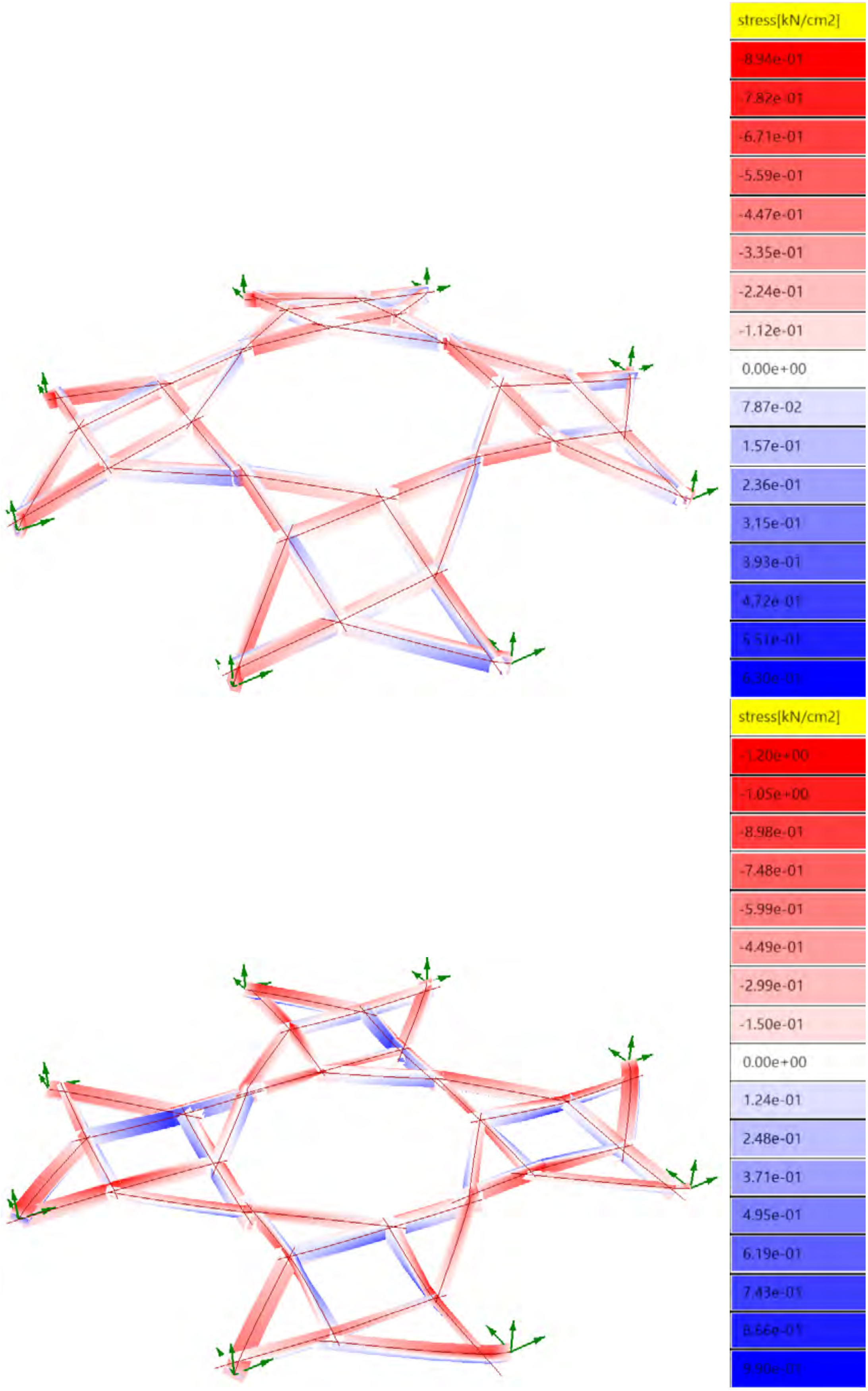

Figure 6.32: Axial stress distribution of reciprocal lace structure from Karamba analysis, rigid connections (left) and semi-rigid connections (right)

Variations The Reciprocal Lace does not yield as many possibilities for variations of the geometry as the previous concepts. Here the variations are rather made by changing the dimensions of the elements used and the number of elements used. By increasing either the height of the individual elements of the number of elements the curvature of the structure would be increased.

6.3.5 Result Comparison

In figure 6.33 a comparison between the three concepts based on the results of the digital analysis is shown.



	SCISSOR OCTAHEDRON		RECIPROCAL LACE		TENSEGRITY WEAVE
MATERIAL	56x270 mm	56x270 mm	140x315 mm	140x315 mm	75x75mm
CONNECTIONS	Rigid	Semirigid	Rigid	Semirigid	30mm (wires)
MASS TOTAL	4.4 ton	4.4 ton	2.1 ton	2.1 ton	4.1 ton
DEFLECTION	39 mm	128 mm	15 mm	130 mm	119 mm
UTILISATION					
Tension	8%	9%	0%	0%	54%
Compression	8%	8%	18%	15%	32%
Bending	56%	67%	43%	58%	
Shear	32%	37%	100%	87%	

Figure 6.33: Results from analysis of the three concepts performed with Karamba

7

Evaluation of structural concepts

The evaluation of the three structural concepts was firstly based on the geometric application of the concept. Given that the inspiration comes from textiles, the possibility to make a structure which is geometrically adaptable to a random surface, through the repetition of modules or joints, is important. Secondly the concept were evaluated based on their load bearing capacity, architectural qualities, feasibility etc.

The concept were first evaluated separately and later compared to each other in an evaluation criteria matrix.

7.1 Evaluation Criteria

The evaluation criteria, not in order of priority, used to evaluate each concept were:

- Geometric Applicability
- Ease of modelling and calculation
- Architectural qualities
- Material efficiency
- Ease of assembly/ building
- Resilience

Geometric Applicability As mentioned above, the first evaluation criteria was the geometric applicability. This includes how easily the concept may be adapted to a given surface by addition of modules in different directions as well as *how easily this adaption can be modelled and made.*

Ease of modelling and calculation included how easy it is to assemble the concept in a digital model, as well as to calculate the load capacity of the concept.

Architectural qualities was the subjective evaluation criteria where how beautiful and interesting the structure is for the viewer was taken into account. Kinetic behaviour of the structure was included as a positive feature in section.

Material efficiency included how much material is needed in comparison to the resulting strength of the structure.

Ease of assembly was an evaluation criteria taking into account how easy each concept would be to assemble on site in full scale. If the structure could be prefabricated on another site and transported to the site, is for example a positive feature.

Resilience included how sensitive the structure is to imperfections. If one piece of a module breaks, does the entire system break as well or is it still stable?

7.2 Evaluation of Octahedron Scissor Textile Structure

Evaluation of Scissor Octahedron Structure

GEOMETRIC APPLICABILITY	MATERIAL USE	DEFLECTION	EASE OF DIGITAL MODELLING	EASE OF ASSEMBLY	ARCHITECTURAL QUALITIES	REDUNDANCE
+ Orthogonal grid which is adaptable to the case.	4.4 tons per 100 square meters	128 mm	- Complicated to modell one module digitally, hinges and connection points .	+ Deployable, can be built on other site and deployed on site.	- Orthogonal, resembling a traditional truss.	- Rather sensitive structure overall.
			+ Orthogonal	- Large amount of objects.		
			+ Possible to copy one module to a structure system.	- Need of tightening joints after deploy		
				+ Many identical objects		
				- High demand on accuracy in assembly process		

Figure 7.1: Evaluation of octahedron scissor structure

The concept of the Octahedron Scissor Structure was rather easy to apply geometrically to the case. However it is also a sensitive structure with low redundancy, built up by many objects. The large number of objects implies a difficult building process though as the scissor structure is deployable, much of this process could be done off site. The scissor structure's deployability was a very interesting feature. When assembled and put in place however, the structure is rather similar to classic truss structures. Furthermore, it lacks the clear connection between function and form, thus the architectural qualities are low.

7.3 Evaluation of Tensegrity Weave Structure

Tensegrity is a very interesting concept with architectural qualities of both an interesting pattern and a visual connection between function and form. For the orthogonal case study in this research it was however not easily applied. The digital

Evaluation of Tensegrity Triaxial Weave

GEOMETRIC APPLICABILITY	MATERIAL USE	DEFLECTION	EASE OF DIGITAL MODELLING	EASE OF ASSEMBLY	ARCHITECTURAL QUALITIES	REDUNDANCE
- Triangular pattern not suitable for this orthogonal case.	4.1 tons per 100 square meters	119 mm	+ Rather easy to model digitally	+ Identical objects, easy to mass produce	+ Interesting pattern	- One module alone very sensitive
			- Difficult to obtain correct pretension.	- High demand on detailing joints where tension can be adjusted.	+ Clear visual connection to tension and compression	+ Redundant in surface assembly.
			+ Easy to calculate load capacity	- Constructed on site	+ Kinetic properties retained.	
				- Many objects		

Figure 7.2: Evaluation of tensegrity triaxial weave structure

modelling of this concepts was rather easy since it is based on a geometry of a repetition of the same module. The repetition of modules also enables mass production of elements since only two kinds of bars are used. However, the assembly on site would be a time-consuming and complicated process. The elastic properties of the structure makes it more redundant to single elements breaking since the structure would automatically form find itself again. Being constructed by some elastic members also makes this concept retain some kinetic properties.

7.4 Evaluation of Reciprocal Lace Structure

Evaluation of Reciprocal Lace

GEOMETRIC APPLICABILITY	MATERIAL USE	DEFLECTION	EASE OF DIGITAL MODELLING	EASE OF ASSEMBLY	ARCHITECTURAL QUALITIES	REDUNDANCE
+ Orthogonal and symmetric	1.2 tons per 100 square meters	159 mm	- Difficult to obtain the hierarchy between elements.	+ Few elements	+ Very interesting pattern	- All elements depend on the next
- Need of support in the same plane, i.e. need of edge beams			+ Modular assembly possible.	- Must be constructed on site	- Too large object in this case	
				- Reciprocal, may be complicated construct.		

Figure 7.3: Evaluation of reciprocal lace structure

The reciprocal lace was concluded to be a very interesting concepts. However, the scale of the structure lessens the architectural qualities and a larger number of modules in smaller scale would give it a more intriguing pattern. The orthogonal way of assembling makes it fitting for the case in question. The fact that the reciprocal structure needs support from all sides however, is a disadvantage. The reciprocal lace structure could be made from one and the same material depending on the design of the joining between elements and potentially no extra small joints are needed. This concept also proved to have a rather low material need.

7.5 Comparison of Concepts

Evaluation Criteria Matrix

	WEIGHT	SCISSOR OCTAHEDRON	RECIPROCAL LACE	TENSEGRITY WEAVE
GEOMETRIC APPLICABILITY	6	5	1	3
MATERIAL USE	5	1	4	2
DEFLECTION	0	2	1	3
EASE OF DIGITAL MODELLING	1	1	1	4
EASE OF ASSEMBLY	3	2	3	1
ARCHITECTURAL QUALITIES	4	3	4	5
REDUNDANCE	2	2	1	4
		58	**54**	**63**

Figure 7.4: Evaluation matrix, comparison between the three concepts

The three concepts were compared to each other through the use of an evaluation matrix. In this matrix each category of the evaluation has been ranked from most important to least important. The most important feature was given 6 points and the least 0, to weight the importance of the evaluation criteria. Each concept was given points, with regard to each evaluation criteria, from 1 to 5 where 1 is bad and 5 points is very good. The points given in one criteria was multiplied with its weight point and a total scoring calculated.

In this evaluation, the geometric applicability has been assessed as the most important evaluation criteria. The aim of textile informed structures has been to make a structure able to "grow" in multiple directions and cover an arbitrary surface, due to the configuration of the repetition of joints. Thus, the geometric applicability of the structure is crucial. The geometric applicability of each concept was assessed with regard to the case study. Possible geometric variations or alternatives were disregarded in this comparison.

For this specific case, the scissor octahedron structure was assessed to be the most suitable in terms of geometric application. Being based on an orthogonal grid and able to grow in the orthogonal directions it could easily be adapted to the roof geometry. Since the tensegrity concept also can grow in multiple directions, but does not follow the orthogonality of this case, it is assessed to be rather easily adapted to the case but not too much. The reciprocal lace is, though with the orthogonal logic, poor in this regard as it needs support along all sides to cover the roof surface in this specific case.

Since these kinds of structures could be a light-weight alternative to classic roof structures with large beams and slabs, the material use was also ranked quite high. The material use was calculated as the weight of each concept using the lowest possible of the available standard dimensions of timber, and the smallest possible diameter of the tension cables for the tensegrity structure. In this case, the scissor octahedron structure used the least amount of material. The evaluation of material use was strictly a comparison based on the weight of each structure covering a surface of 10x10 m. Only the structure was counted, and any kind of covering was excluded.

The architectural qualities, ranked as the third most important criteria were assessed subjectively based on the opinions of the authors. These three highest ranked criteria are key when proving textile informed structures is an alternative to the classic structures. Due to the evident visual connection to function, as well as its interesting pattern, the tensegrity weave was ranked as the best in this regard.

The evaluation of the ease of assembly for the different concepts were based on the intuition and discussions between the authors. The main issues defined as; whether or not the building objects could be mass produced, if the structure could be prefabricated and the complexity of the joints. Both the scissor octahedron structure and the tensegrity weave contain a large amount of objects, which implies a time consuming process. A scissor structure could be built off site and be deployed on site. However, the joints would need to be tightened after deployment to obtain a more stable structure, which would be a very time consuming process. The reciprocal lace structure contain fewer objects but would need to be constructed on site due to its reciprocal nature. In the end all concepts were assessed to be rather difficult to assemble, but the reciprocal lace structure regarded as the best due to its few elements.

Deflection was ranked as the least important due to the different behaviours of the concepts. Specifically the tensegrity weave structure was designed to retain some kinetic behaviour and thus the deflection is not a clear sign of breakage. Therefore, it was weighed with zero in this particular evaluation.

In terms of redundancy both the scissor octahedron structure and the reciprocal lace structures have been shown to be rather sensitive structures. The tensegrity weave on the other hand would adapt and alter its form to obtain equilibrium after breakage of one element and was thereby considered rather redundant.

The comparison made shows the tensegrity weave as the best alternative to the case study.

8

Discussion

In this study, clear parallels between textile assembly methods, classic geometric principles and structural systems have been drawn. The general idea of textiles as a repetition of joints, as well as more detailed analysis of specific types of textile and their bindings, have been mapped onto large scale structural systems. The general idea of textile was translated to a scissor structure derived from the geometric form of an octahedron. Based on the analysis of the thread paths in textile, these threads have been translated into structures with rods, tension band and beams. The pattern of clockwise or counter-clockwise turned cells in a woven or braided textile was translated into reciprocal and tensegrity structures, both following the same logic. The thread path in a weave cell was translated to a tensegrity module, and a triaxial weave system based on one and the same tensegrity module of three was constructed. Finally the thread path of one binding in a plain hole bobbin lace was mapped into a reciprocal module of eight objects.

Each structural concept, i.e. the octahedron scissor structure, triaxial tensegrity weave and the reciprocal lace structure, are built up by modules which can be attached to each other in two or three directions. Since all of these modules are based on a structural system, the modules are designed to be stable on their own. When assembling these according to the textile logic, based either on geometry or thread paths, the modules retain their stability.

Structures which follow this logic, being a repetition of joints, are able to grow in multiple directions. This was shown to result in structures which, based on a single module or a combination of very few modules, could be adapted to cover arbitrary surfaces. However, in the concepts evaluated in this thesis, only simple geometrical patterns were evaluated and tested. Looking at each concept from a top view, they consist of a square pattern (the reciprocal lace and octahedron scissor structure) or a combination of triangles and hexagons (in the triaxial tensegrity weave). There is a great potential to vary the geometry of these surface geometries by varying the modules geometric form. More dome-like structures could be achieved by using combinations of geometric forms as base for the different modules. Using combinations of hexagon and pentagon modules for example - as in a football, yield a dome shape. This way of thinking gives a large range of possible variations to adapt to any irregular space.

Each concept also shows much potential for controlling the global assembled geometry through making alterations to each module. Aiming to create an arched, or dome-like shape, the local geometry of one single module could be altered. In tensegrity modules the length of the tension cables could be used to control the geometry. By shortening the tension bands in the lower side of the modules, the global geometry will arch. In reciprocal structures, the geometry is instead controlled by the sizing of each element, with elements of a larger cross sectional height, the entire structure will arch more. In the concept of the octahedron scissor structure, the arched form can be attained by moving the joints downwards along the elements, thus creating a polar motion of the structure when deployed.

Each concept was shown to work in the analysis conducted in this study. However, these examples are made on a simple case with a number of simplifications. Detailing of joints and members have not been conducted in this research but would be needed going further. The digital analysis of the concepts was made using timber, for compressive and bending elements, and steel, for tension cables, assuming fabric to be used for covering. While there is the possibility to exchange these materials, timber and fabric in particular, for other kinds of materials, they were chosen for their light-weight and wide availability in Sweden.

Textile is, in architecture and civil engineering, a rather unexploited material relative to its potential. The main focus of this report, the textile logic, has been shown as a wide source of inspiration to large scale structures. The main possibilities of a textile informed structure are identified as:

- To make a geometrically adaptable structure, with potential to cover arbitrary surfaces
- Interesting architectural qualities
- Mass production of simple building elements
- Producing lightweight structures of small building elements
- New way of thinking to realise a span over a surface - membrane surface versus hierarchical structures spanning in first one direction then the other, e.g. beam structures
- Demonstrate how one could bring inspiration from one field of engineering research into another

8.1 Further research possibilities

There is a large potential for future research, both in terms of detailing and further development of the concepts presented. Furthermore, great possibilities lie in the exploring of other concepts using the method presented in this thesis.

In terms of mapping or translating textile into structures the following structures could be further researched:

- Mapping of 3D braids
- Multiple basic lace patterns which are not yet evaluated
- Mapping of layered 3D weaving
- Three dimensional textile structures - exploring possibilities of textile informed structures using a more three dimensional assembly method, combining the knowledge gained here with further developments of platonic solids
- Three dimensional weave structures using the theory of tensegrity in combination with the geometry of platonic solids

To further develop the concepts presented in this thesis the following future research possibilities have been identified:

- Construction and detailing of members and joints in tensegrity structures to facilitate assembly
- Construction and detailing of members and joints in scissor structures to facilitate assembly and deployability
- Construction and detailing of members and joints in reciprocal structures to facilitate assembly
- Development of a parametric work flow/plugin to apply these structure onto an arbitrary surface

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