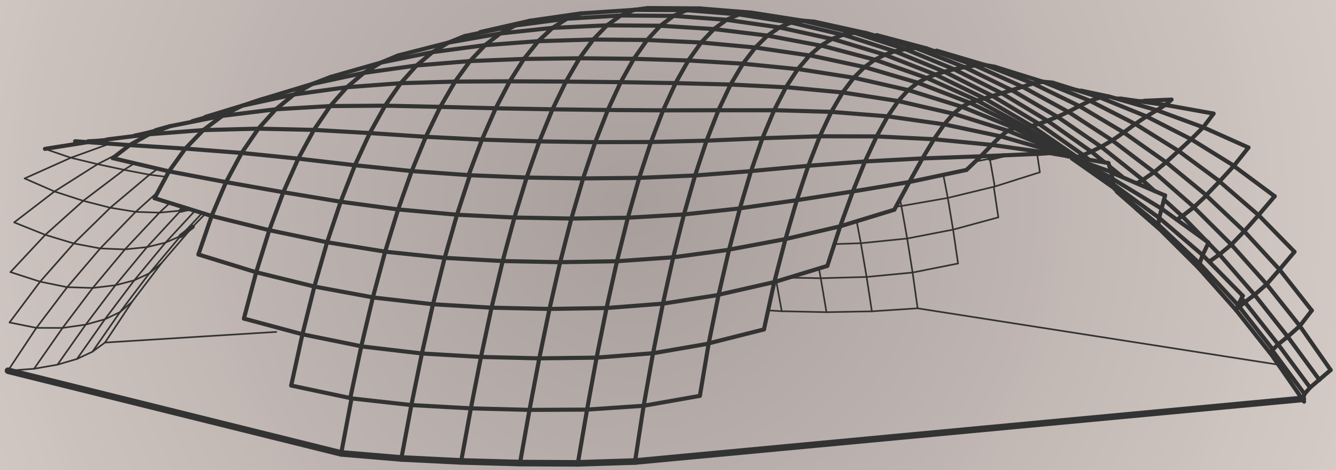
GRIDSHELL

MANUAL



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This project is inspired by the work of the gridshell.it group. A special thanks to Sergio Pone, Sofia Colabella and their team!

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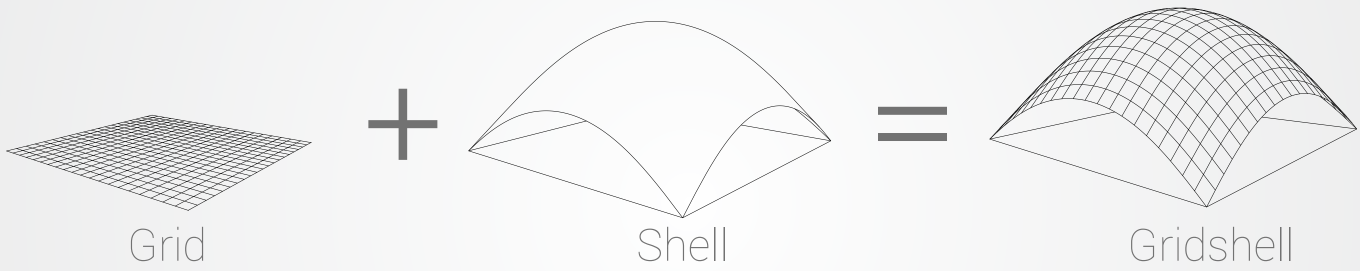
WHAT IS A GRIDSHELL?



EXPLAINATION

A gridshell is a structure which derives its strength from its double curvature (in a similar way that a fabric structure derives strength from double curvature),
but is constructed of a grid or lattice.

Wikipedia

WHAT IS A GRIDSHELL?

Shortly said, a shell is a construction type that carries loads through membrane forces, or in-plane stresses, rather than bending and shear forces. While a concrete shell is a continuous surface, a gridshell is divided in a grid of smaller elements.

A way to create gridshells are the kinematic construction process. It consists of building a rectangular or quadratic grid flat, and then deform it into shape by pulling together or lift parts of the grid. Wood is an appropriate material, because of its good bending attributes. It is fairly simple to construct a timber gridshell out of straight elements

The model and process described in this manual, is based on this construction method.

Why gridshell?

The main reason to pick a gridshell construction is not only based on performance, efficiency and cost, but on architectural shape. Based on a gridshell, one can construct spectacular shapes and characteristic buildings. In addition you have got the spatial attributes, which is important for the use of the building. A self bearing construction gives flexibility in the interior.

How gridshell?

The shape of the gridshell must be structural, which demands an understanding from the architect and collaboration with the structural engineer. One can not make decisions solely based on design ideas but have to do it in harmony with the structural shape. Also, the structure must be stable during the whole construction process.

This model and process described in this manual, describes how designing and construction could be done in such a manner.

Anchor Points is the same as foundation.

Bending strength,see Flexural strength.

Catenary is the shape of a hanging chain or cable supported at the ends. The inverted shape is ideal for compression only structures. The shape is also called funicular. (See page 12).

Compressive strength is the capacity of a material or structure to withstand loads tending to reduce size.

Curvature is a measure of how a line deviates from beeing flat. See Radius of curvature.

Dynamic relaxation is a numerical method that can be used for form finding for cable and fabric structures. By adding different forces, it aims to find a state, or geometry where all forces are in equilibrium.

E-module, see Youngs Modulus.

An **Elastic modulus** is a number that measures an object or substance's resistance to being deformed elastically (i.e., non-permanently) when a force is applied to it. it includes Young's modulus (E), Shear Modulus (G) and Bulk Modulus (K).

Equilibrium is a state when the system (eg. a gridshell) is in balance, resulting in no internal shapual change.

Flexural strength is defined as a material's ability to resist deformation under load. Flexural stress causes both compressive and tensile stresses, and is similar to tensile strength for homogenous materials. See page 36.

DICTIONARY

Finite Element Method, or FEM is simply said an advanced method of structural analysis. It divides the structure into smaller parts, finite elements, and adds material values and loads to calculate load distribution.

Funicular, see catenary.

Grasshopper is a graphical programming plugin for Rhino. See page 50.

a **Particle spring system** is a method of formfinding, that is a collection of points collected by springs and acted on by external forces. This method is implemented in our process using Kangaroo for Rhino.

Radius of curvature is mathematically the inverse of curvature, R=1/k. It is on a point on a curve, defined as the radius of a circle that best approximates that curve. The maximal bending of a wood lath is defined with a 'smallest possible' radius. (See page 36).

Rhino is a NURBS based CAD software. (See page 50).

Tensile strength, or Ultimate strength is the maximum stress a material can withstand beeing stretched or pulled.

Karamba is an element analysis plugin for Grasshopper. See page 50.

Kangaroo is a physics engine plug-in for Grasshopper. See page 50.

The **segment-lath** is the "weaved" lath-principle developed during this master-thesis.

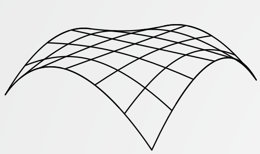
Shear modulus describes a material's response to shear stress and is defined as the ratio of shear stress to the shear strain.

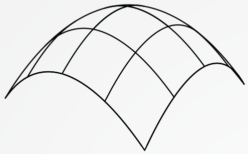
Young's modulus is a measure of stiffness of a material, along an axis to the strain. For material properties of wood see page 36.

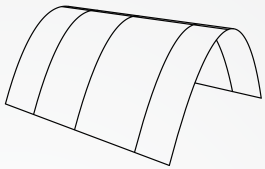
Definitions from wikipedia

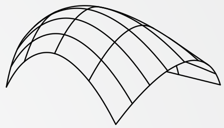
THE SHAPE

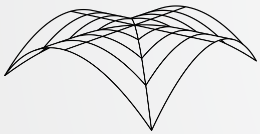
Good and bad shape

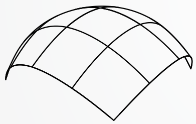

1: Bad shape

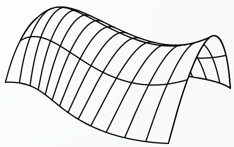

2: Good shape

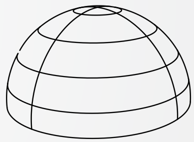

3: OK shape


4: Good shape


5: Bad shape


6: OK shape


7: Good shape


8: OK shape

EXPLAINATION

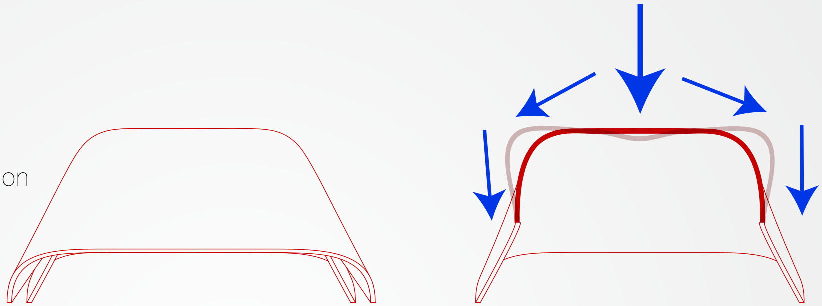
There are many different parameters that decides if it is a good shape or a bad shape. Generally, form follow function, but when it comes to gridshells, forms mostly follows forces.

1. Bad because it is too flat on the top.
2. Good because it is doubled curved.
3. OK because it is very curved in one direction, but is straight in the other.
4. A good, doubled curved shape. A good shape doesn't have to be symetrical.
5. Only singled curved and has kinks in it's curvature.
6. OK shape, but not good because the edges are cantelivering too much.
7. Good. Curved in two directions.
8. Concidering only shape, it is perfect, but it is not possible to create a gridshell like that from a flat grid.

Why good shape, why bad shape

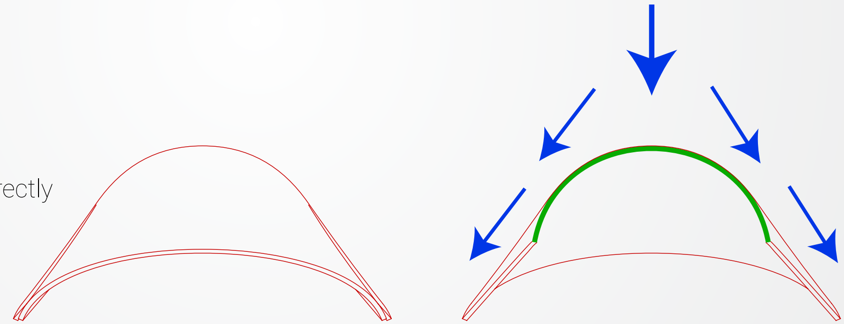
Flat top

Is unfavoruable and can lead to deformation



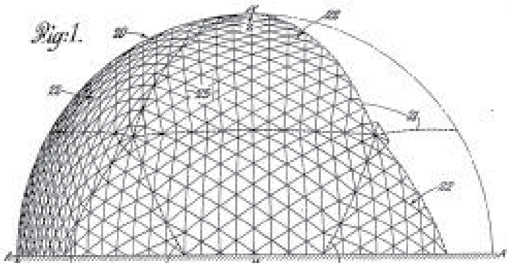
Tall arc

A clear shape distributes the forces correctly



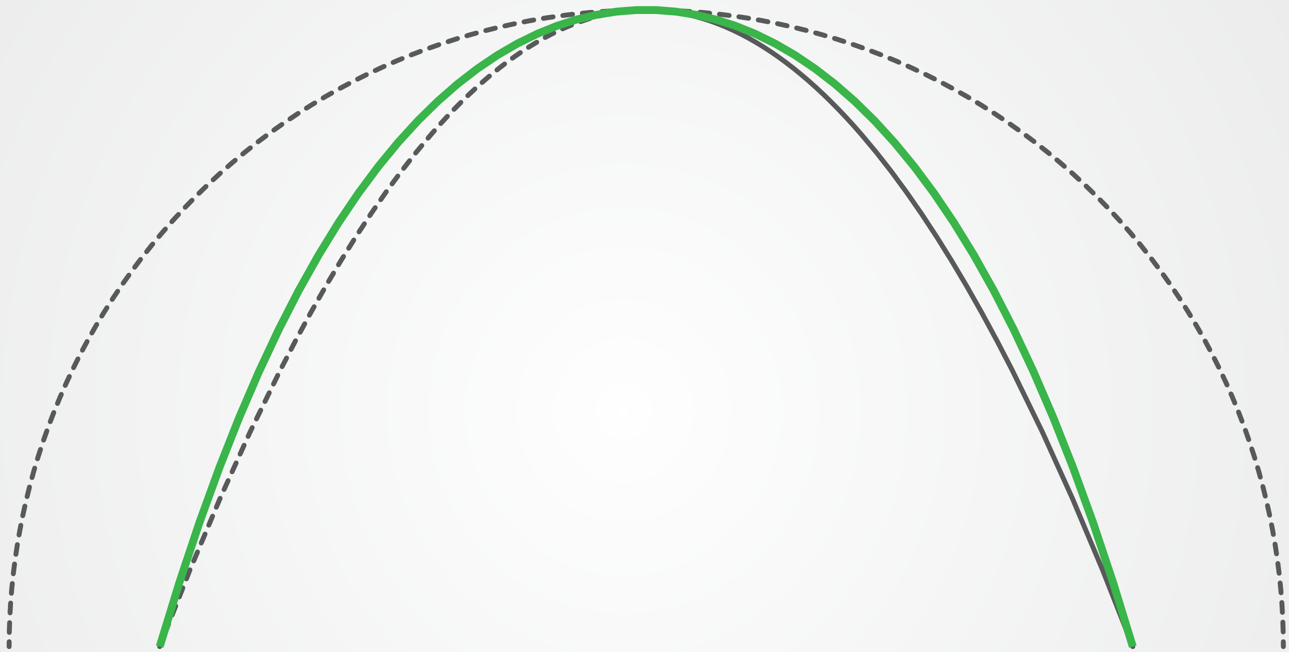
EXPLAINATION

The most important check to do on your shape is controlling top area. If it gets too flat, it will function more like a beam than a shell, and will more easily deform.



The optimal shape would be a spherical dome, but this shape is impossible to deform from a flat grid. Drawing: Buckminster Fuller

Curve Principles



EXPLAINATION

The circle and the parabel are easy to draw, but the catanary curve is the perfect curve for eaven load distributrion.

Wikipedias definition:
In physics and geometry, a catenary is the curve that an idealized hanging chain or cable assumes under its own weight when supported only at its ends.

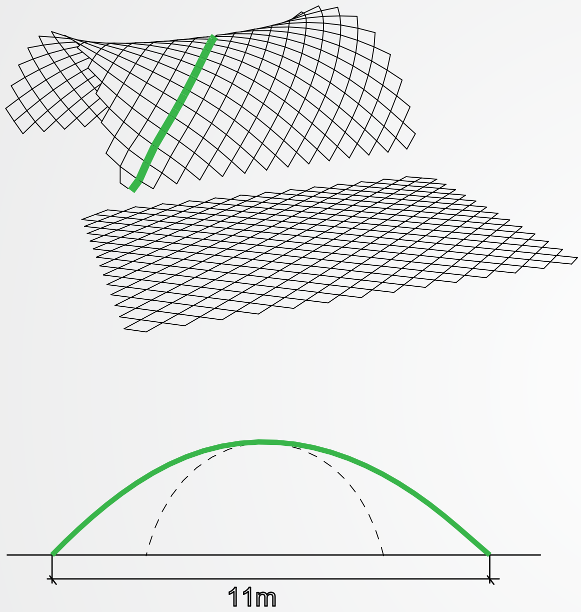
Catanary curves works only in tension. When flipped the curve will be in compression. Since the shell is very thin, it doesn't have any bending capacity and has to absorbe most forces through compression.

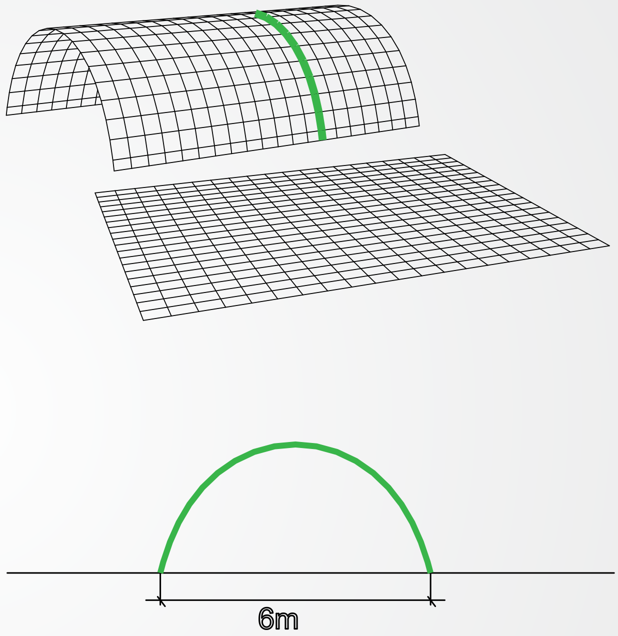
Taking into account material parameters, such as bending capacity, we also know that this shape is not optimal for gridshell.

Curve principles

P: Kamel 15, wikipedia

Diagonal vs orthogonal grid



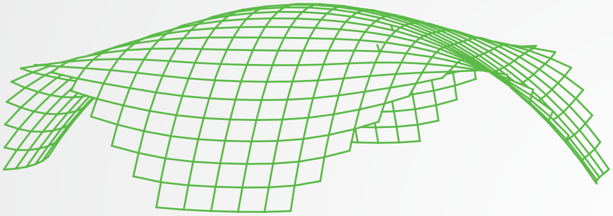


EXPLAINATION

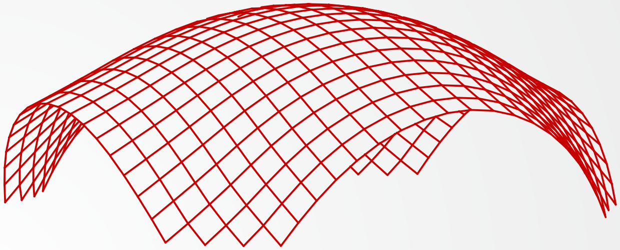
An important design parameter is to choose either an orthogonal or a diagonal grid-layout. The same geometry can have totally different results. As the example shows, the orthogonal grid has laths that has the same curvature as the shape it self. But the diagonal laths are much less curved.

The diagonal pattern can be useful when designing small gridshells. This because the bending capasity often is the biggest challenge.

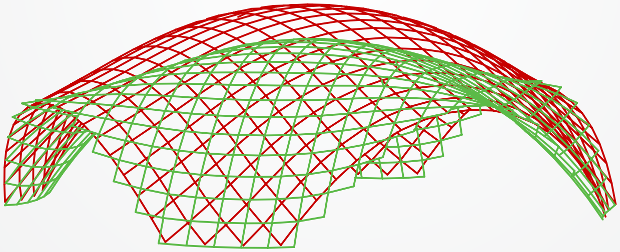
Diagonal vs orthogonal grid



Diagonal



Orthogonal

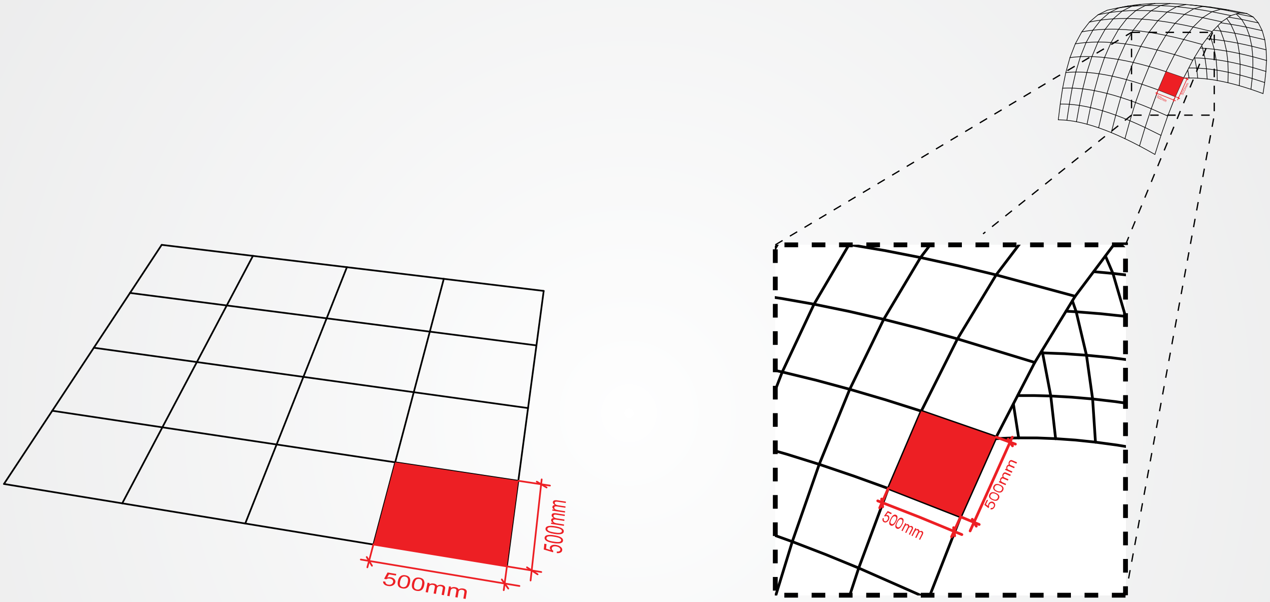


EXPLAINATION

Both examples above have the same anchorpoints and the same original grid properties.

The grid-direction determines how the forces are being distributed through the laths, and this affects the form-finding of the shape.
The orthogonal grid is pushed to the limits of its curvature, while the diagonal gird still can handle a taller top and smaller distance between anchors.

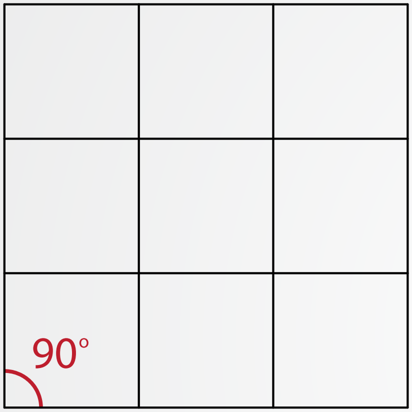
Fixed grid dimension

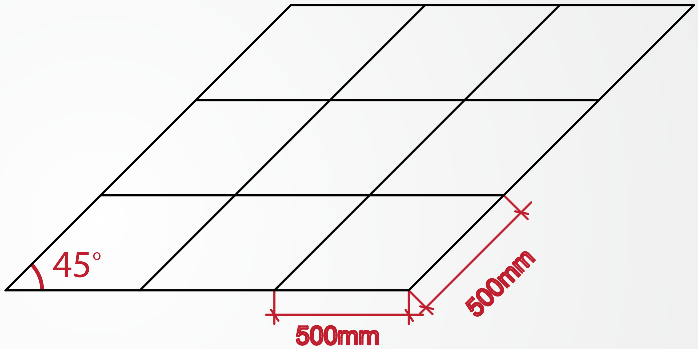


EXPLAINATION

An important precondition is that every member in the gridshell has a fixed length. This counts for both the flat grid, during the shaping and for the final shape.

Fixed grid dimension

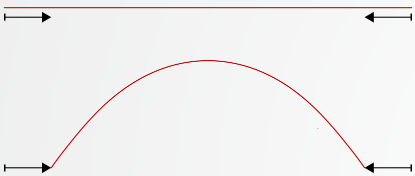


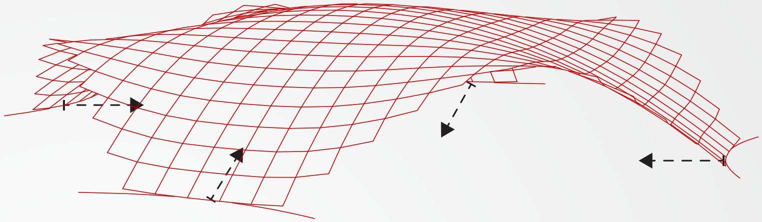


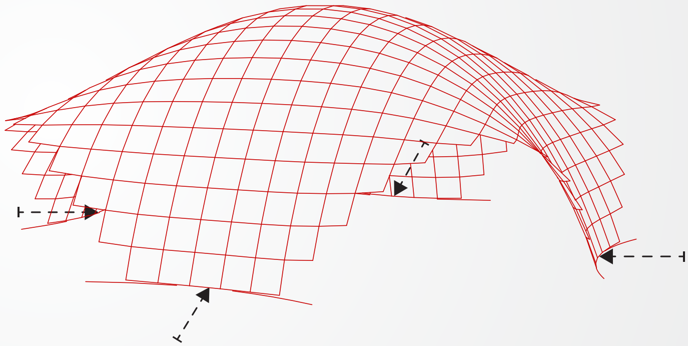
EXPLAINATION

Every joint in the gridshell should allow normal rotation. This is important to be able to form the shape from a flat grid. When the shape is set, diagonals can be attached to lock the shape.

Anchor point controlled



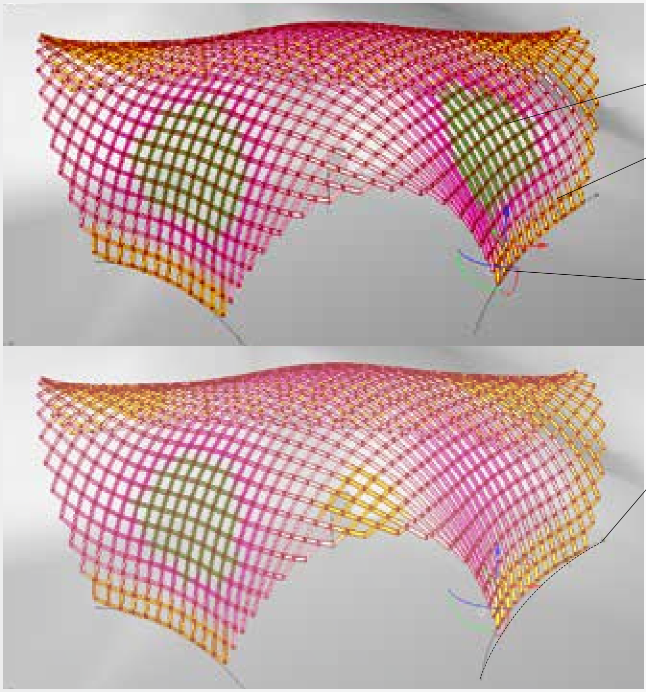




EXPLAINATION

The kinematic construciton process is done by forcing a flat grid into its shape.
A key element in this process is placing the anchor points. In addition to the material carachteristics of the wood, this is what shapes the structure.
In the same way a line (straight beam) takes the shape of a curve when pushing the ends together, the flat grid takes the shape of a shell when the anchorpoints is moved. See more at page 63.

Small changes - big impact



Green indicates high (relative) deformation.

Yellow indicates no (relative) deformation

Moving the center of the anchor line 30 cm changes the load distribution dramatically

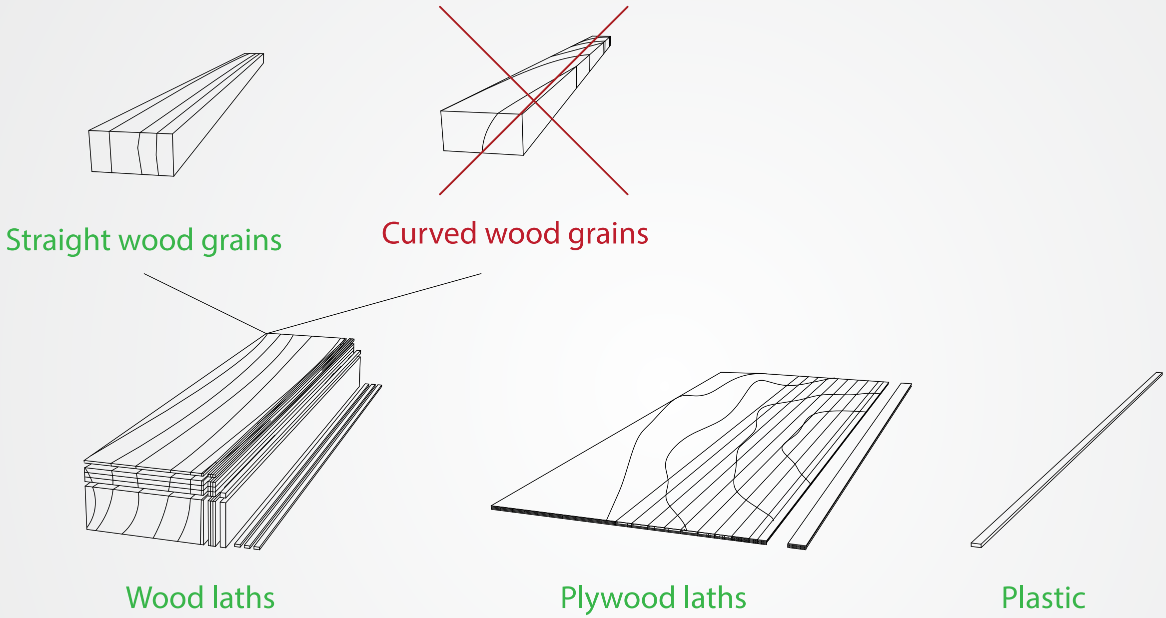
Knowing what a good shape looks like, and how to control it is very important

EXPLAINATION

These screenshots from Karamba shows that small anchor-point transformations, leads to big deformation changes.
Moving the center of the anchor-line 30 cm, removes the large deformations (green color).
This is why it is very important to replicate the digital shape as good as possible. Small differences changes the load distribution totally.

SCALE MODELING

Scale model materials

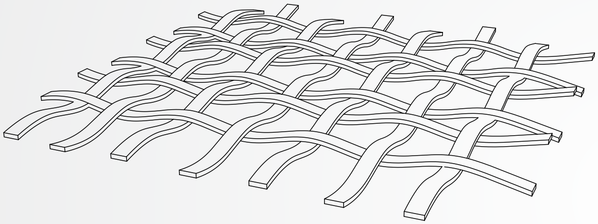


EXPLAINATION

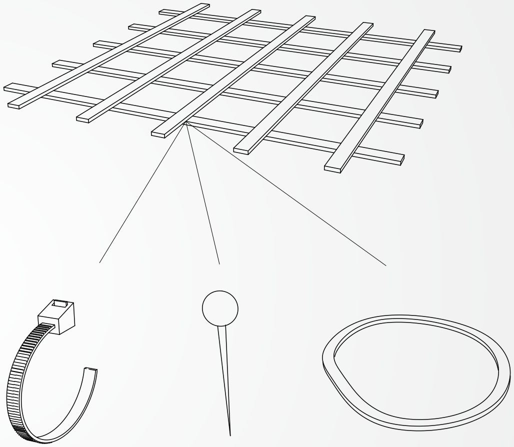
To get a feeling on how forces apply to the grid, scale modeling is recommended.

The best material for building is wooden laths. It is then important to avoid wood blanks with curved grains or knots.

Scale model techniques



Weavning
Fast and flexible



Strips
Slow and stiff

Needles
Slow and stiff

Rubber bands
Slow but flexible

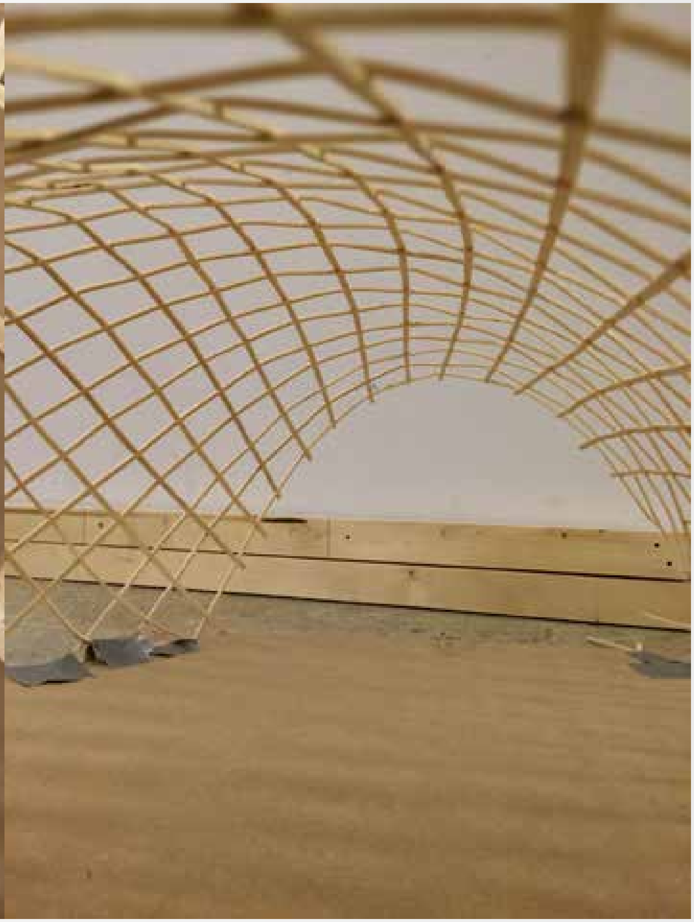
EXPLAINATION

The far best modeling method is weaving. This is only possible with materials with some friction, such as wood or plywood. This tecnhique is the fastest, and it also allows rotation and some movement.

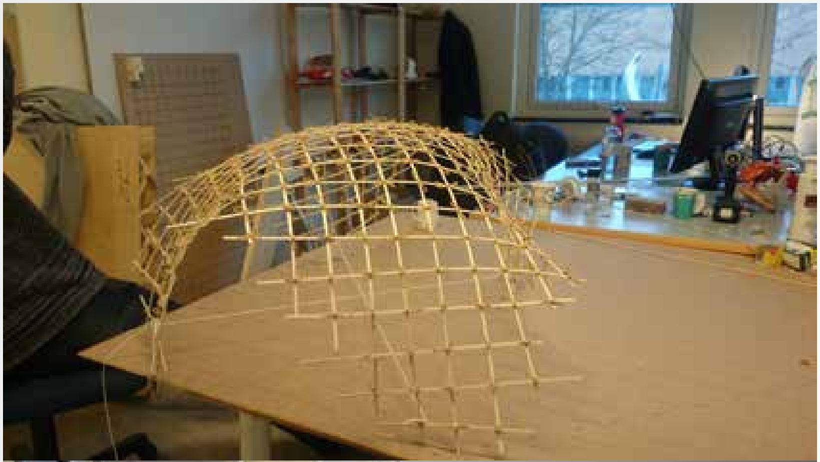
We learned this method from gridshell guru and leader of the research group gridshell.it, Sergio Pone.

Other techniques are not recommended, but the best alternative is to use rubberbands and tie a knot around every joint.

Weaving model technique



Other modelling techniques

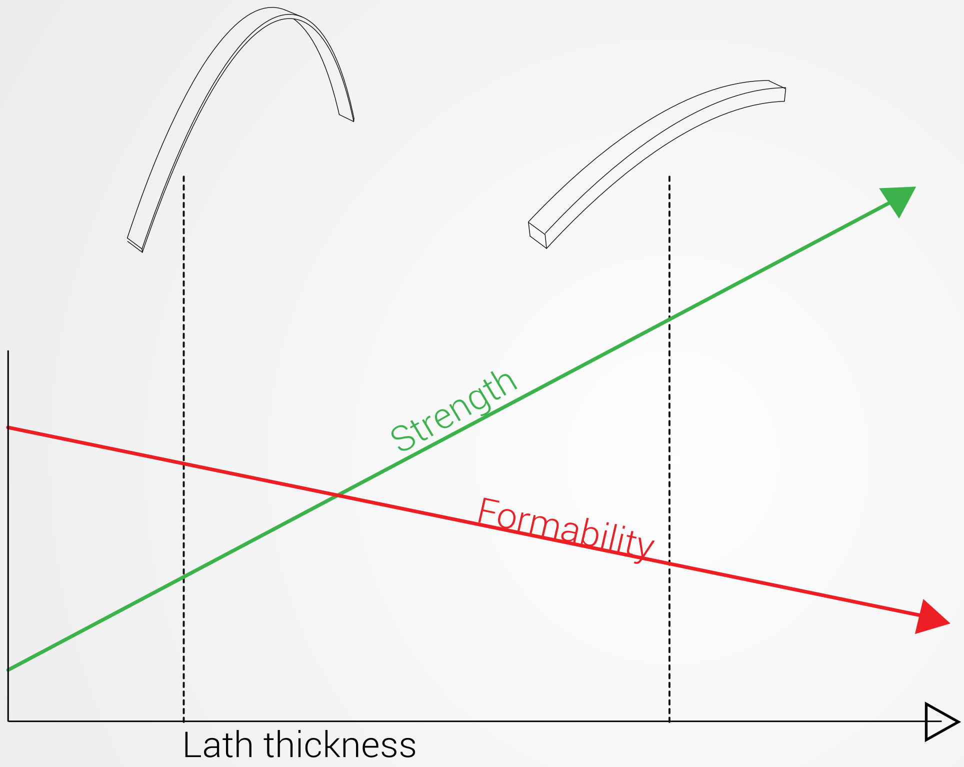


Rubberbands

Needles and screws

DEFINING MATERIAL PROPERTIES

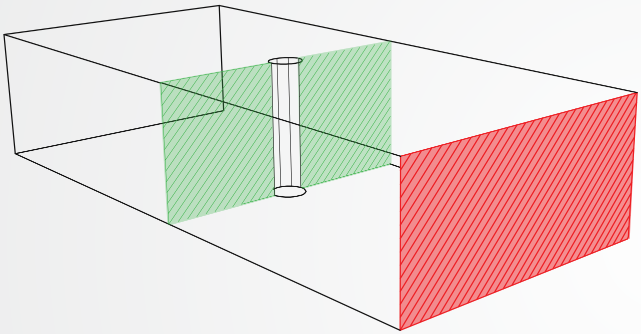
The important balance

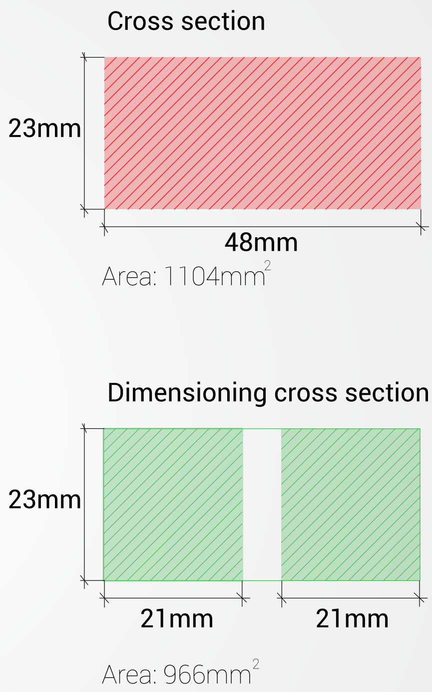


EXPLAINATION

A key element is to find the correct cross-section. Larger cross-section (heigth) increases the strength, but decreases the formability.

Dimensioning cross section





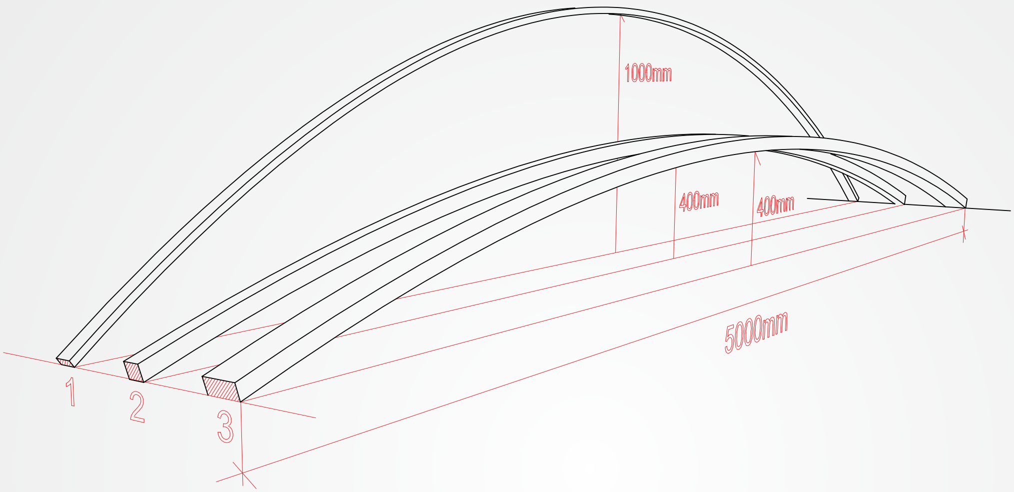
EXPLAINATION

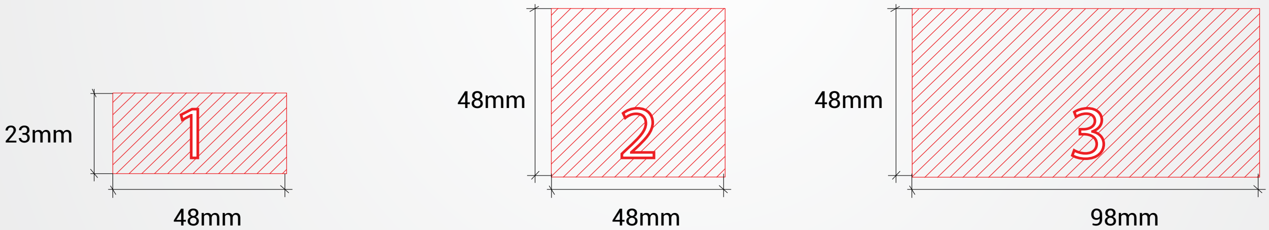
It is important to keep in mind that you remove parts of the cross-section when making holes for the bolts.

Other girdshell projects uses clamps that removes this issue..

P: Carptenter Oak and woodland

Cross-section





EXPLAINATION

As mentioned, the cross-section affects the formability. The relationship between the cross-section heigth and the minimum radius are proportional.

As a practical example: double cross-section heigth, results in a doubled radius.

The relationship are determined by a species/quality dependent constant.

Smallest curvature radius

Different material constants

Strength class	Constant	Cross-section (h)	Smallest radius
C16	250	23	5750
C24	229	23	5267
C30	200	23	4600
D30	167	23	3841
D70	143	23	3289
Segment-lath	152	23	3496

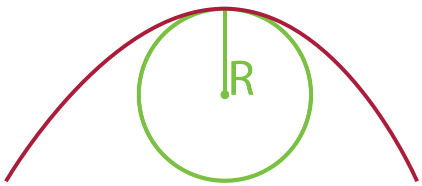
Different cross-sections

Strength class	Constant	Cross-section (h)	Smallest radius
Segment-lath	152	12	1824
Segment-lath	152	24	3648
Segment-lath	152	48	7296

EXPLAINATION

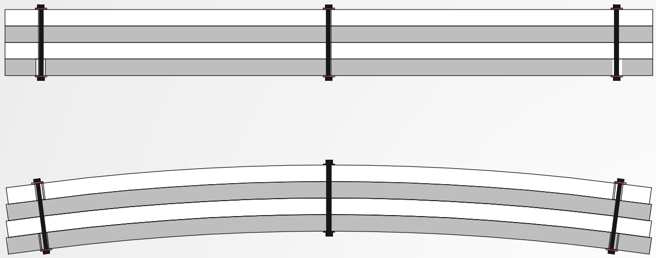
The first table examplifies that similar cross-sections with different timber-qualities results in different radiuses.
The second table examplifies that increasingly cross-section heigths results in larger radiuses.

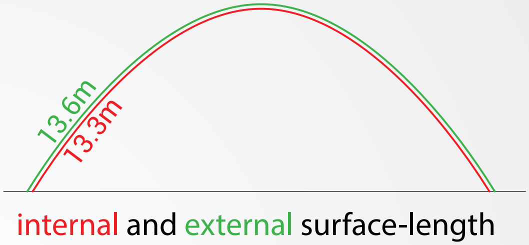
The data (except the segment-lath) are extracted from Thomas Schiøtz Master Thesis, 2013. Data for the segment-lath was measured in a lab-test.

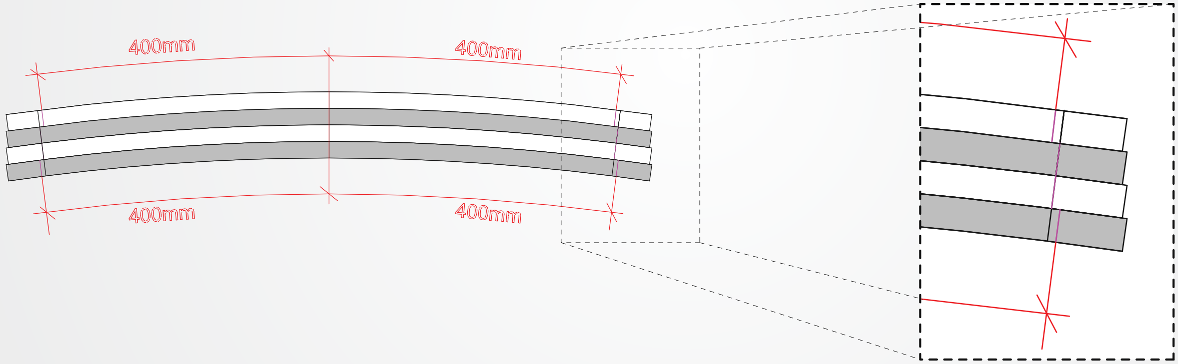


minRadius = Cross-section(h) * Con-

Increasing radius, increasing length







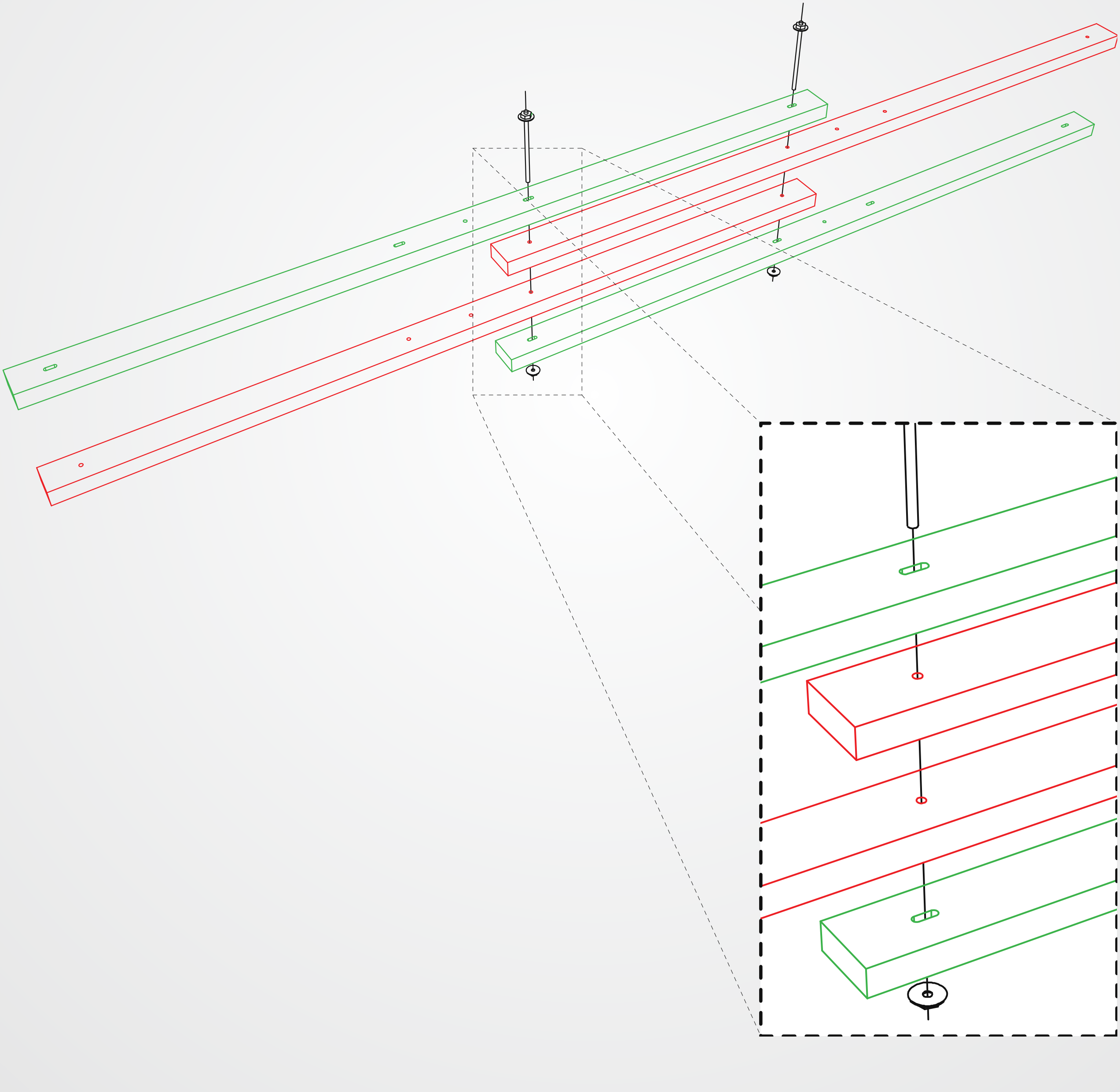
EXPLAINATION

Look at the section of the shell (upper right). The thickness is only 23 mm, but the result is that the inside length of the shell is 0.3m shorther than the outside length.

This problem has to be solved in the detail as well. When the grid is flat, the distance between the bolts are the same, but when curved, there is a longer distance on the outside than the inside.

The detail on the next page shows how the problem is solved with the segment-lath. The bottom and top lath has slotted/rectangular hole. This allows the bolt to slide when shaping the shell. When the shape is satisfying, the bolt is tighten.

Increasing radius - detail example



Material characteristics

Density, wood species (kg/m3)

Balsa	200
Aspen	420
Spruce	430
Pine	490
Birch	580
Teak	630
Oak	650
Pokkenholt	*1200*

Material characteristics in constructon timber

	Bending strength (N/mm2)	E-module (GPa)
C16	16	8000
C24	24	11000
C30	30	12000
D30 (oak)	30	10000
D70	70	20000

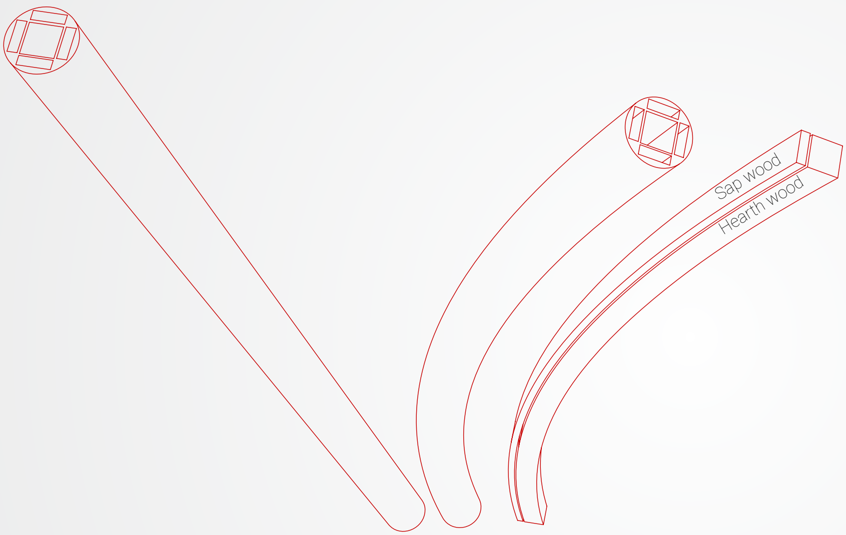
EXPLAINATION

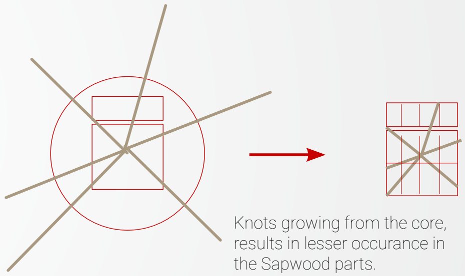
The most important characteristics to look for when choosing material is flexibility, formability and bending strength.

Table 1.
Treteknisk Håndbok, Kapittel 2,
http://www.engineeringtoolbox.com/wood-density-d_40.html

Table 2. Materialegenskaper
for konstruksjonstre, fra EN 338

Choosing the best (part of the) tree





Knots growing from the core, results in lesser occurance in the Sapwood parts.

EXPLAINATION

The conditions the tree has grown in is important. If the forest is dense, it forces the tree to grow upwards instead creating many branches (knots). It is also said that slowly grown trees are stronger than fast grown.

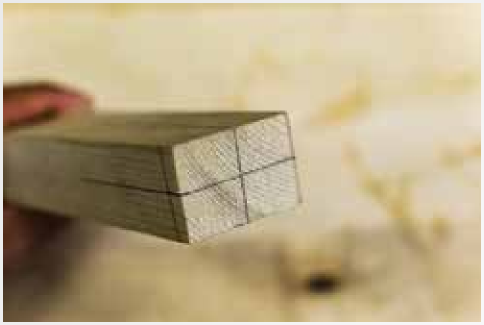
Based on the timber mill`s experience, it is best to use the Sapwood (yteved):
+ More elastic due to longer fibers
+ Less knots
– Not so moisture resistant

Wood species

Characteristics of some species found in Norway
Table from (Berge, 1992)

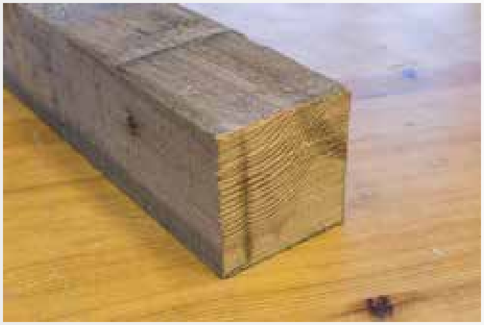
Spruce	Soft, elastic, medium strength, easy to glue and paint, hard to impregnate.
Pine	Soft, elastic, strong, durable, easy to cut and process, hard to glue and paint, can be impregnatet
Birch	Ductile, elastic, low moisture resistance, easy to process,
Oak	Dense, heavy, hard, durable, elastic, semi-hard to process, mosture resistant
Aspen	Soft and loose, fluffing, moisture resistant (strongest dry), no cracking while drying

Wood species



Spruce

Aspen



Pine

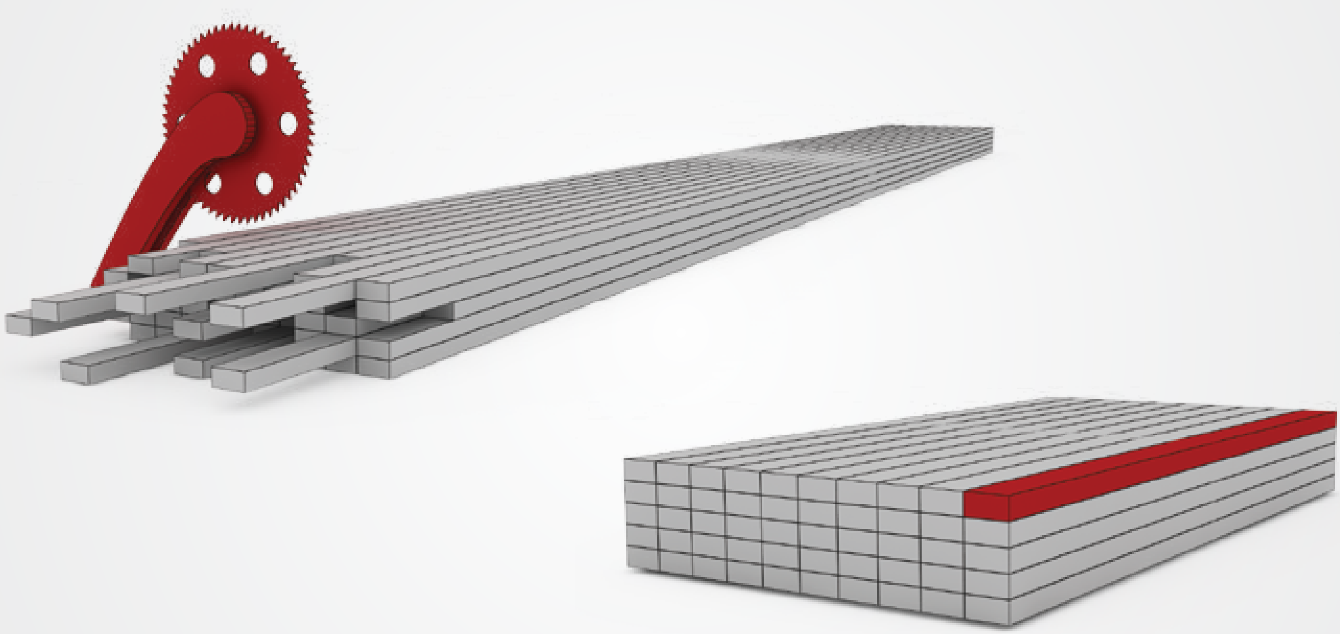
Birch

Oak

RedOak

HOW TO BUILD

01: Precut

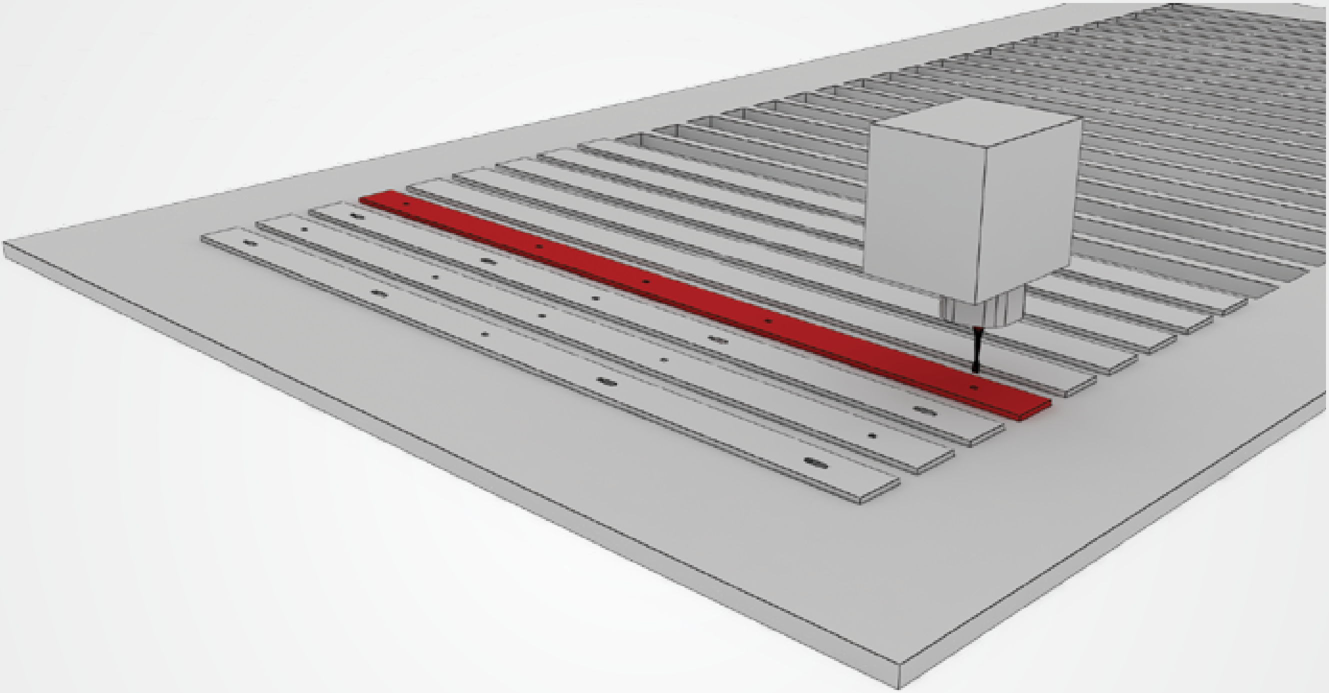


EXPLAINATION

The saw-mill can often precut the timber to desired length.
This is only recommended with well sorted timber with little knots.

An alternative is to precut piece by piece, removing the knots.

02: Cutting holes

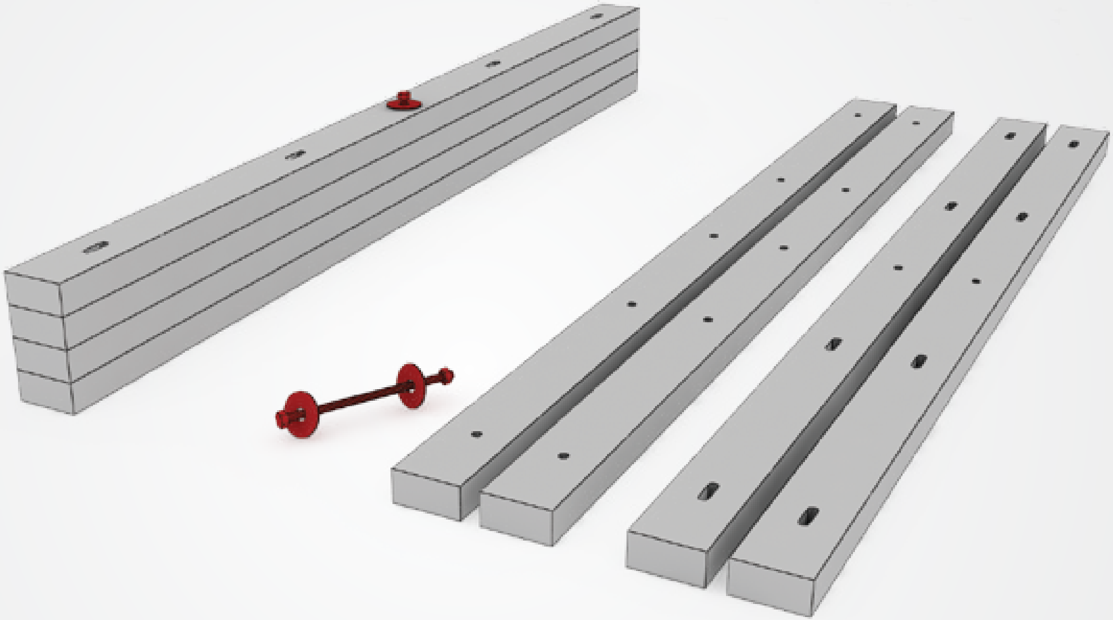


EXPLAINATION

A cnc-mill cuts holes and slotted holes in the laths. 38 laths requires 15 minutes, including off/on-loading. This results in 2.5 laths/minute.

A tip is to create a jig that ensures easy unloading/loading, but still keeps the laths in place.

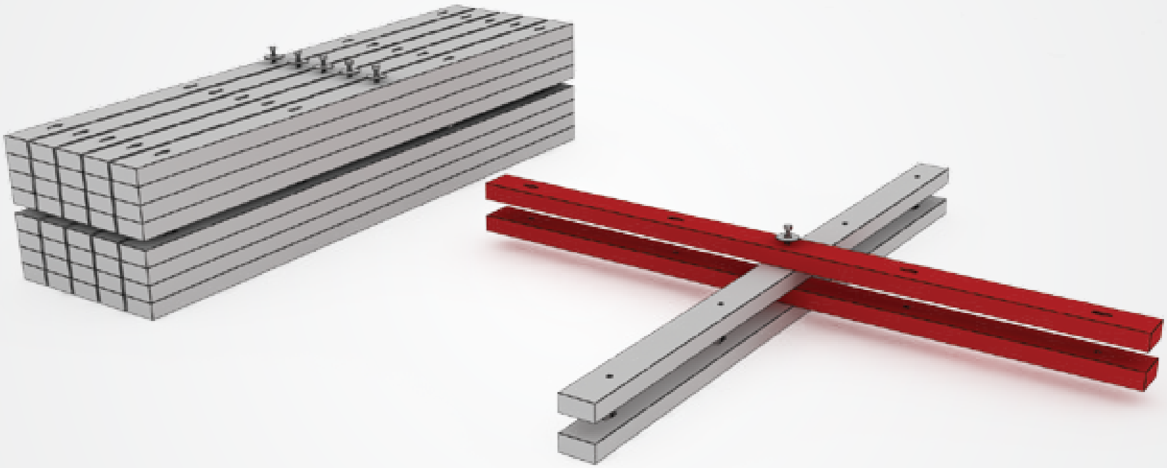
03: Element-assembly



EXPLAINATION

Two laths with slotted holes, two laths with straight holes, one bolt, one nut and two washers creates the element prefabricated in the workshop.
The detailing makes the element very transport-friendly.

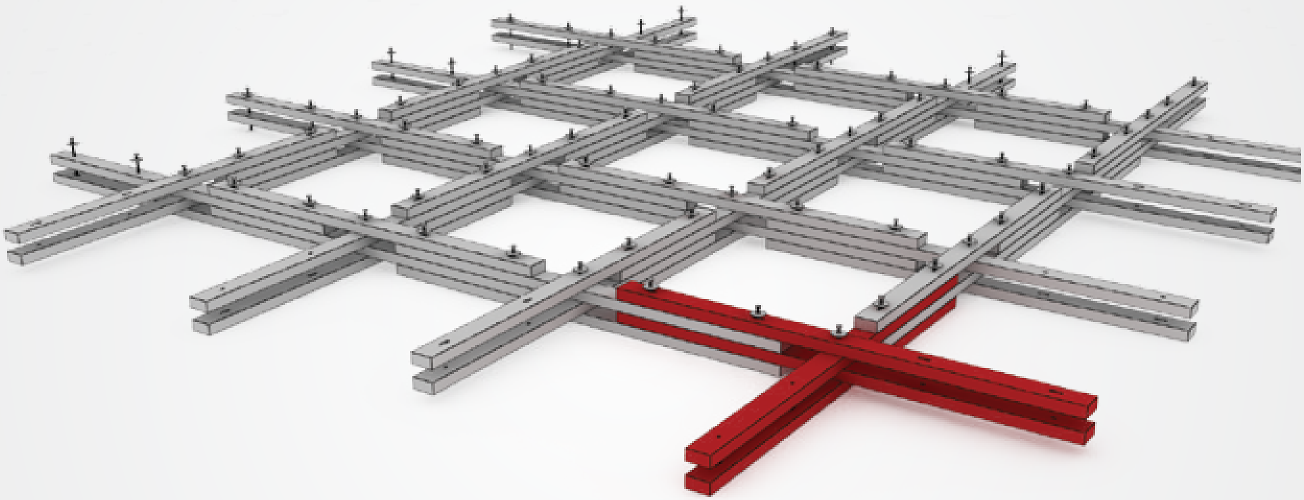
04: The cross



EXPLAINATION

The one cross is the base for the hole gridshell and represent the verticies in the grid.

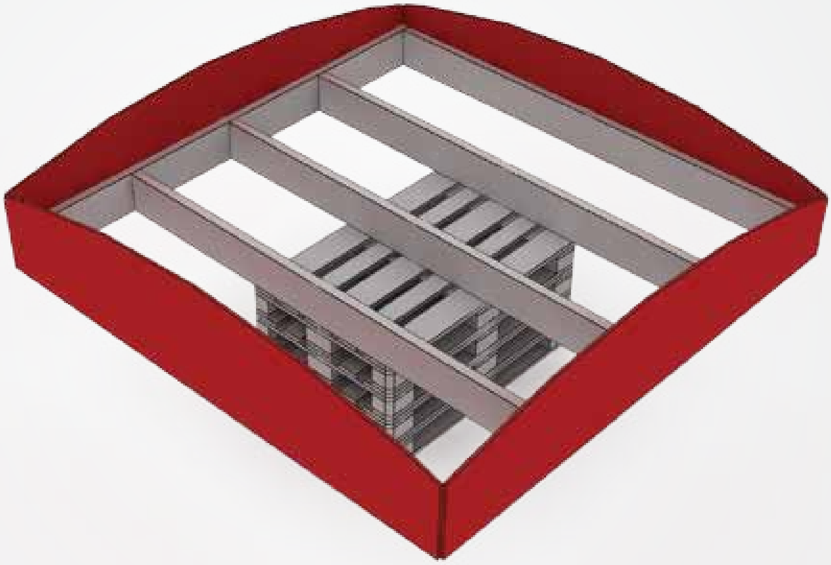
05: Grid-assembling



EXPLAINATION

Weaving the crosses repeatedly, you can create what ever grid-shape you want.
The prefabricated holes maintains the correct grid-size.

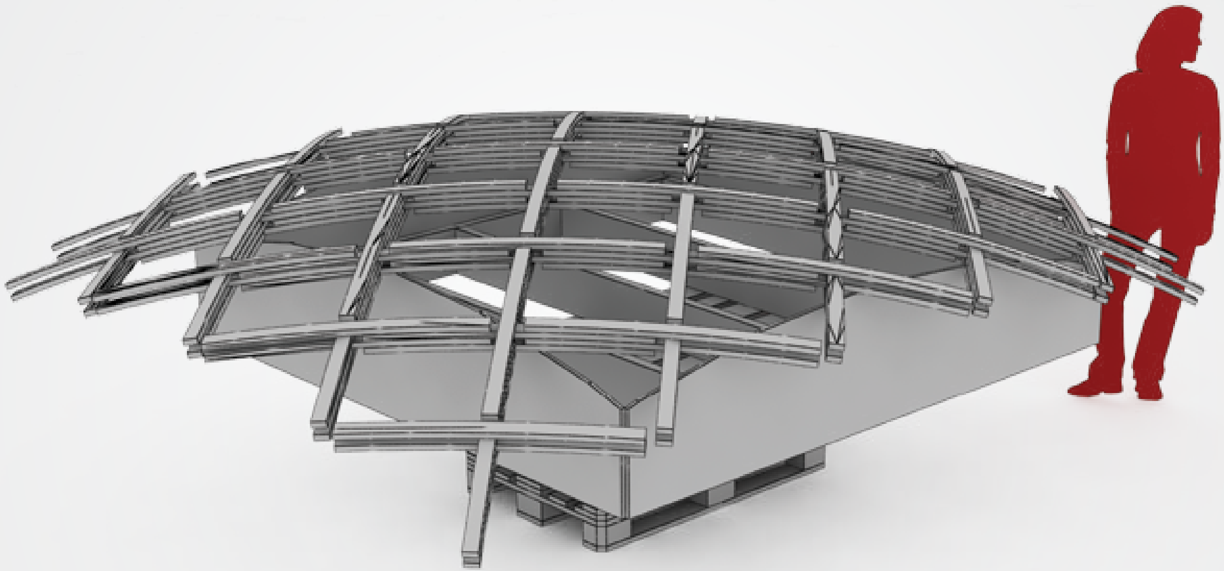
06: Grid-bed



EXPLAINATION

When lifting the grid, it is important to distribute the forces as even as possible. A grid-bed, that replicates the shells final shape ensures an even load distribution.
The pallets underneath are progressively added.

07: Laying the grid

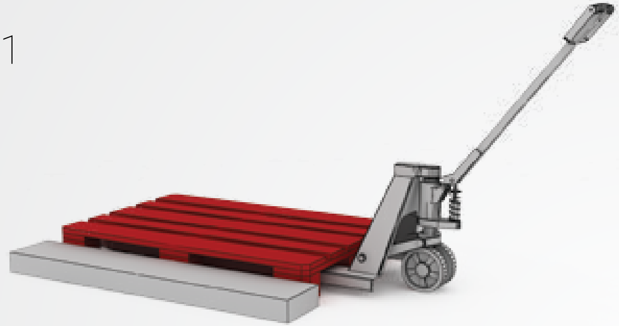


EXPLAINATION

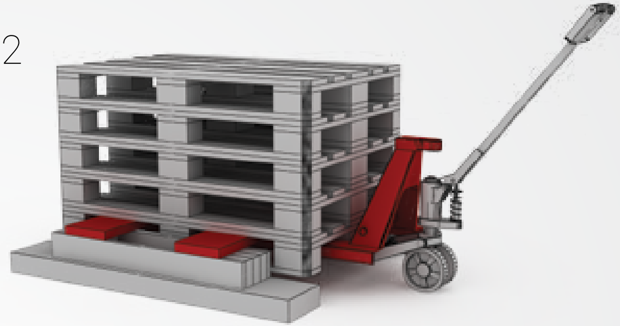
When laying the grid on the bed, it allows the builder to add crosses keeping a good working position.

08: Raising the structure

01



02



03

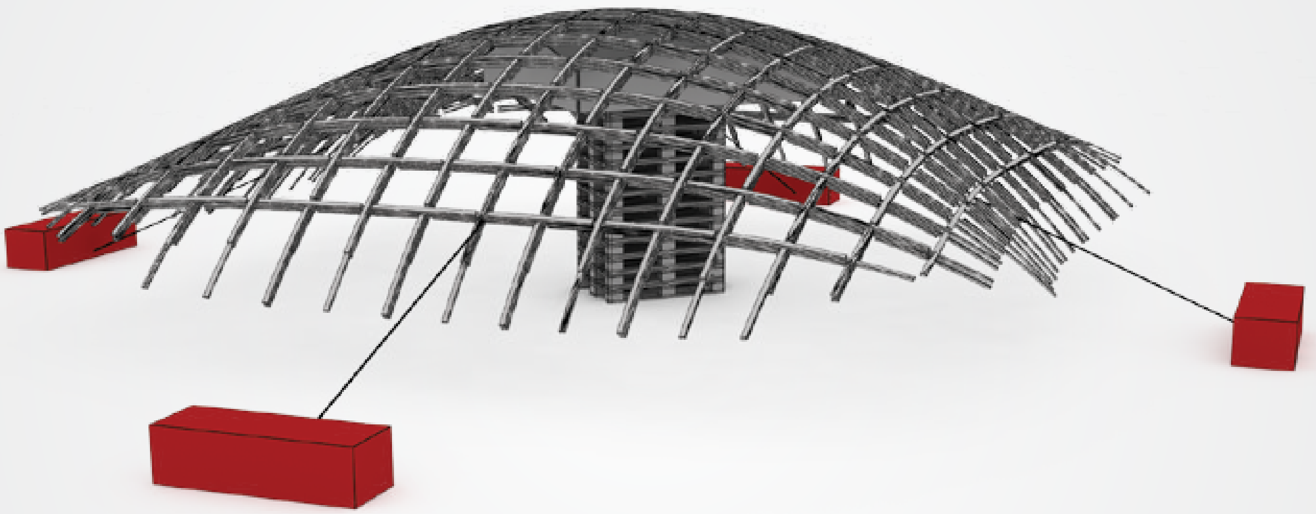
04

EXPLAINATION

Larger structures would of course demand a crane, but low cost-structures can use primitive methods such as a temporary scaffolding or a pallet jack.

Since a standard pallet jack only lifts 120mm and the pallet is 144mm, you need to bypass the load and do the lift in two stages.

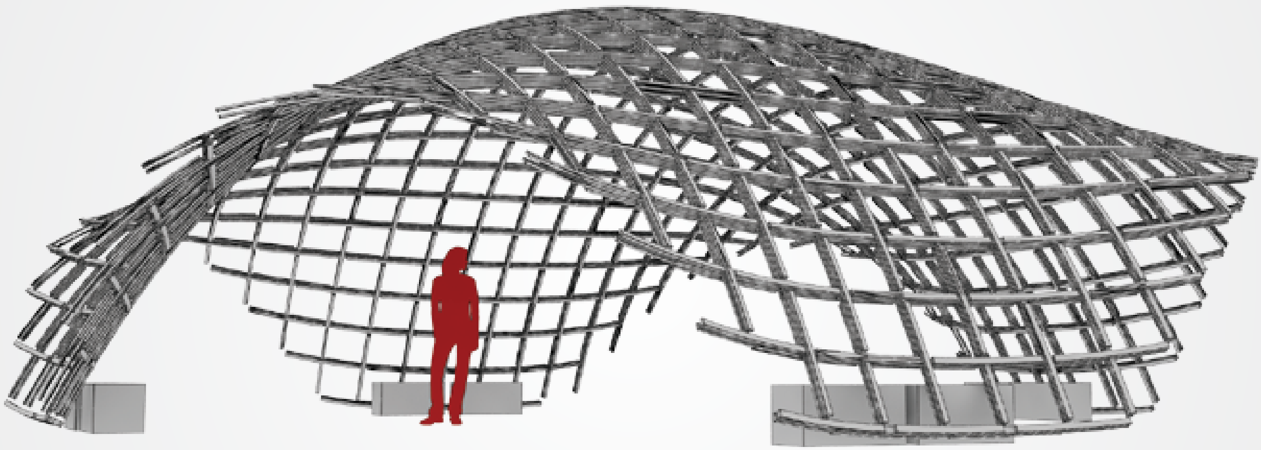
09: Securing the grid



EXPLAINATION

The foundations can be used both to shape and to secure the structure. Temporary columns and bracing can also be sensible to add.

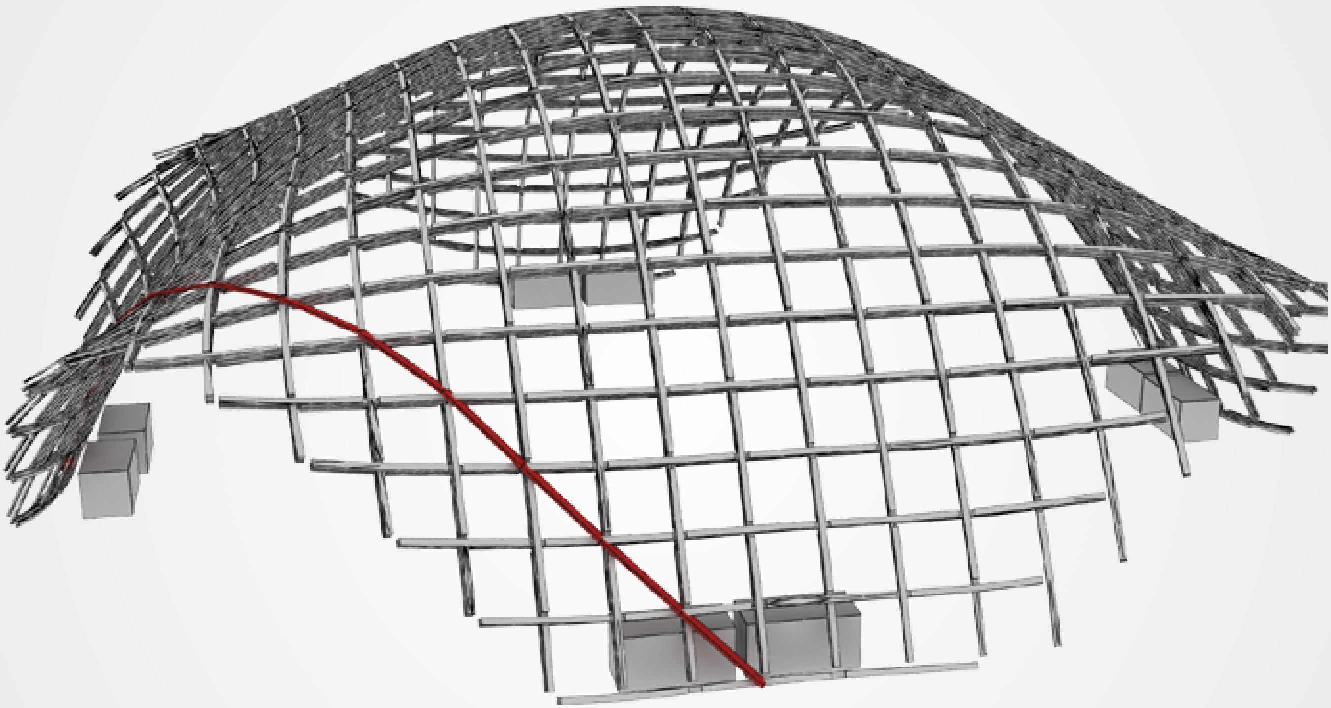
10: Finnishing the shape



EXPLAINATION

It is important to duplicate the digital shape in the real world. Positioning the foundations accurately can make it easier to find the correct shape.

11: Bracing

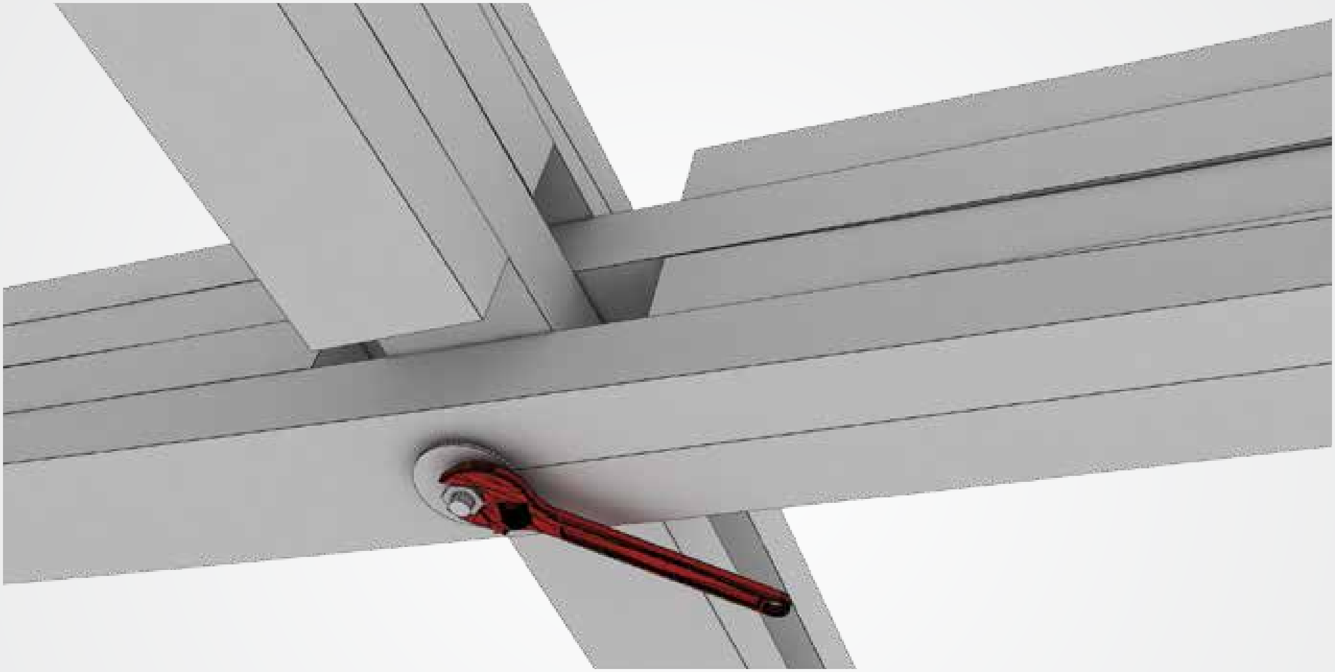


EXPLAINATION

Bracing is important to lock the shape. This decreases the outwards force in the foundation and makes it more resistant to un-eaven loads.

This also assures thattarp will not be disrupted by the bolts.

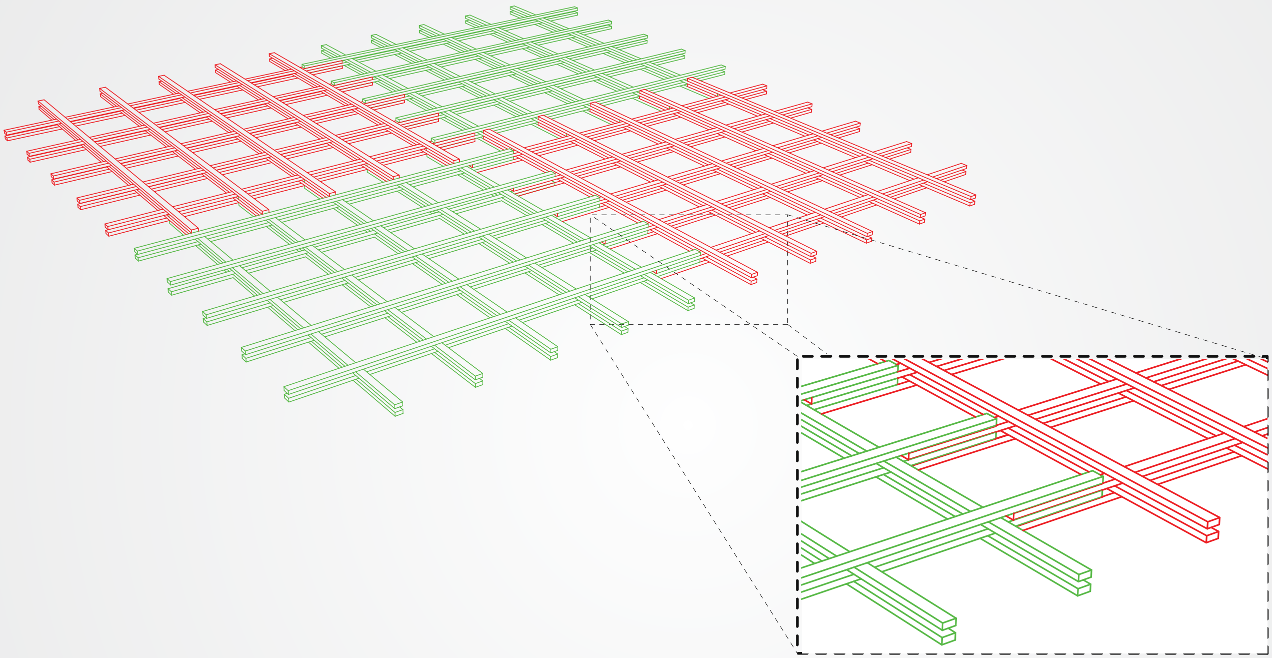
12: Thighten the bolts



EXPLAINATION

The last step is to thigten the bolts.
This joins the laths and makes the structure stronger.

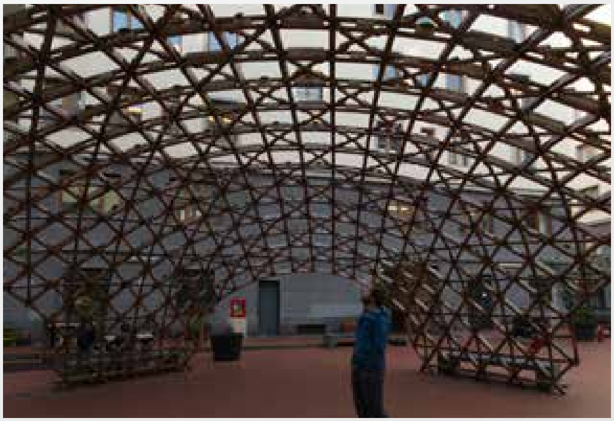
Others: Extending the laths



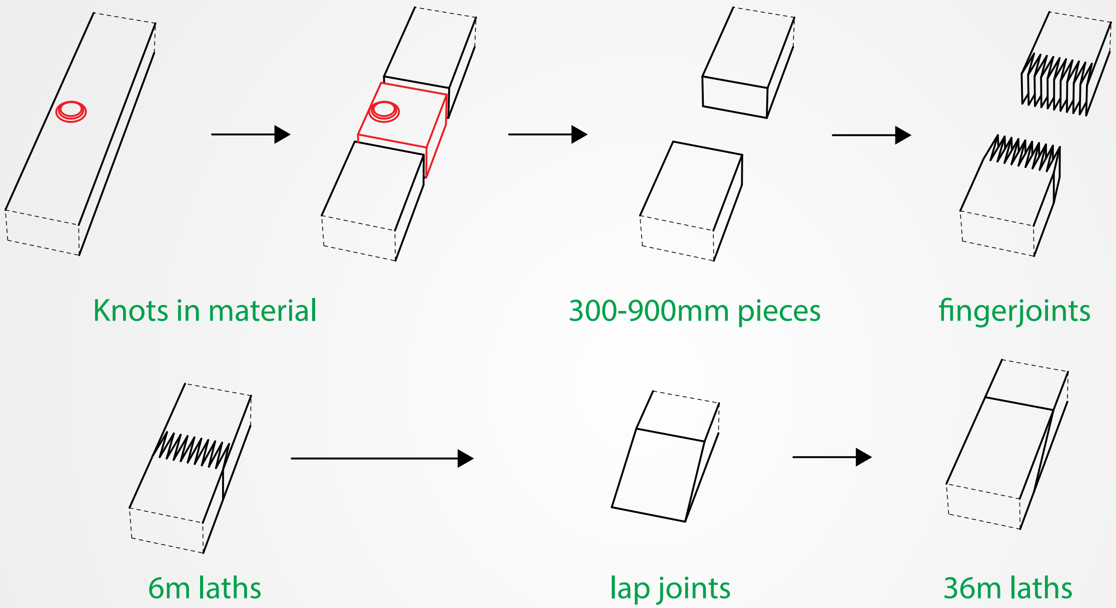
EXPLAINATION

The Gridshell.it team uses a detail where they extend the laths for each fifth grid-lenght.

Our solution, shown earlier, has been developed from this solution, but instead of having the extending as a exception, our detail use it as a design-rule. This makes the pattern easier, more dynamic and more homogenious.



Others: Extending the laths

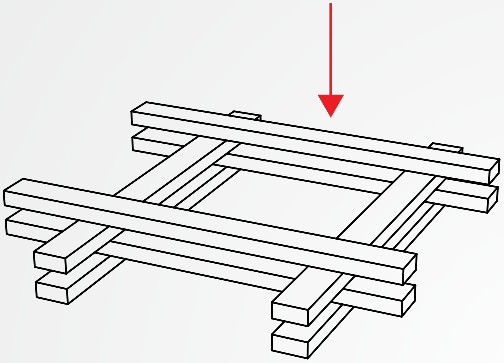


EXPLAINATION

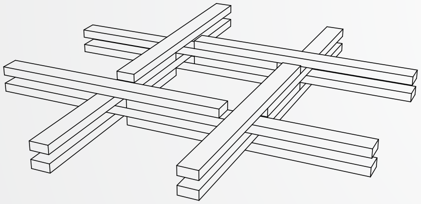
This example is from the building of the Savill garden gridshell. In order to produce knot-free, continious laths up to 36 meters, every piece was cleand free from knots by cutting them into 300mm to 900mm lengths.
They were thereafter fingerjoint to 6m laths at the workshop and then lap joint to its final lenght at the building site.

P: David Baugh

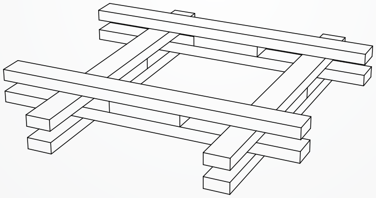
Shear blocks



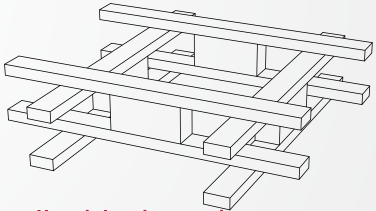
Plain grid has little shear stiffness



Shear blocks through weaving



Same height blocks

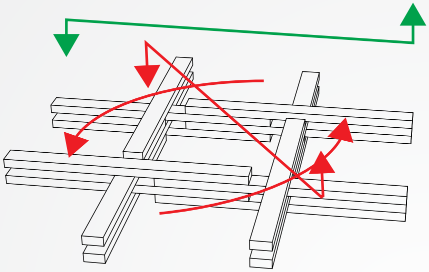


Taller blocks makes an I-profile-like strength

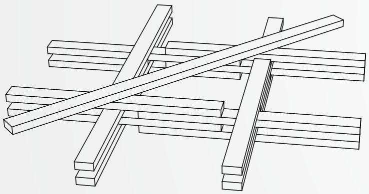
EXPLAINATION

To reduce the “span” of each lath, shear blocks are added. They provide shear stiffnes to the grid, and could also help making a distance between the top and bottom layer, to create a taller cross-section.

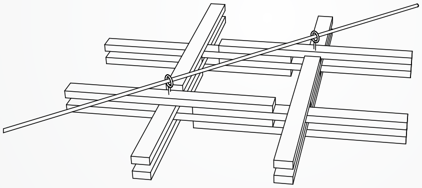
Diagonal bracing



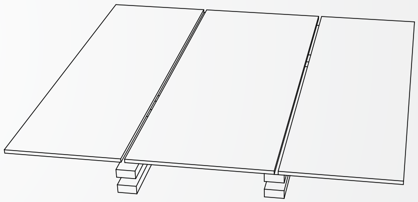
Little in plane stiffness without triangulation



Diagonal laths



Diagonal wires



(plywood) plates

EXPLAINATION

The plain grid has initially no stiffness in its plane. In order to lock the quadrants, it needs to be triangulated.
Triangulating the whole grid is not necessarily needed , and it can be done in different ways.

BUDGET

FINANCIAL (A DRAFT!)

The materials listet are from the built example, 132 m^2. It is important to keep in mind that foundations, tools and unknown costs will be added to a permanent project. Production/Assembling can decrease if more industrialized.
The master-thesis` built project were due to kind sponsors almost free.

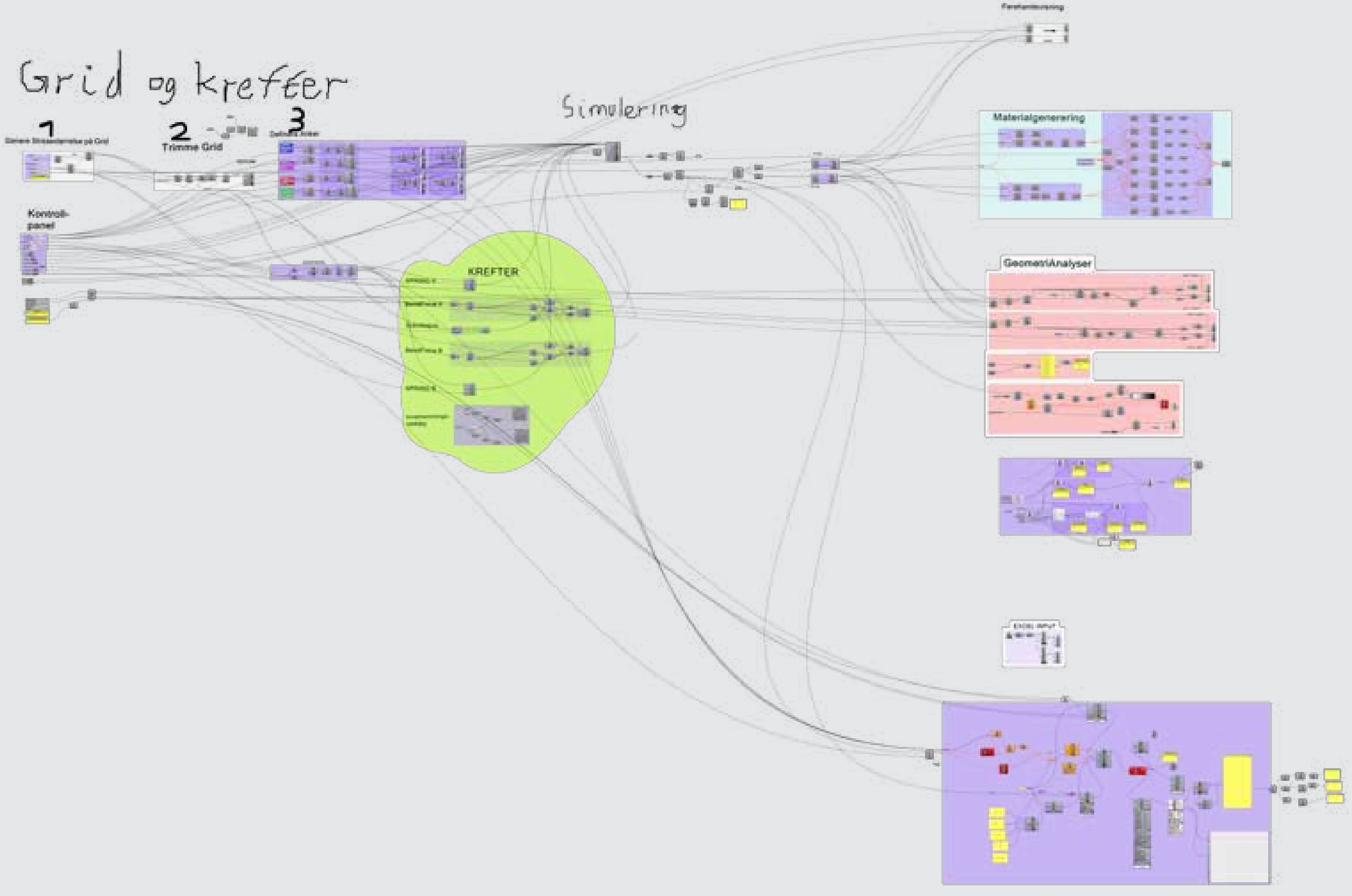
Material	Quantity	Unit price	Price
Timber	2034 m	6.25 NOK	12 712 NOK
Bolts/Nuts	2825 stk	3.00 NOK	8475 NOK
Tarpolin	131.5 m^2	200 NOK	26 300 NOK
Production	40 t	750 NOK	30 000 NOK
Assembling	60 t	500 NOK	30 000 NOK
		TOTAL:	≈108 000 NOK
		Price pr m^2	≈820 NOK

OTHER WAYS TO MAKE SPACE

Area: 90 m^2
Price: 75000 NOK
Price pr m^2: 830 NOK

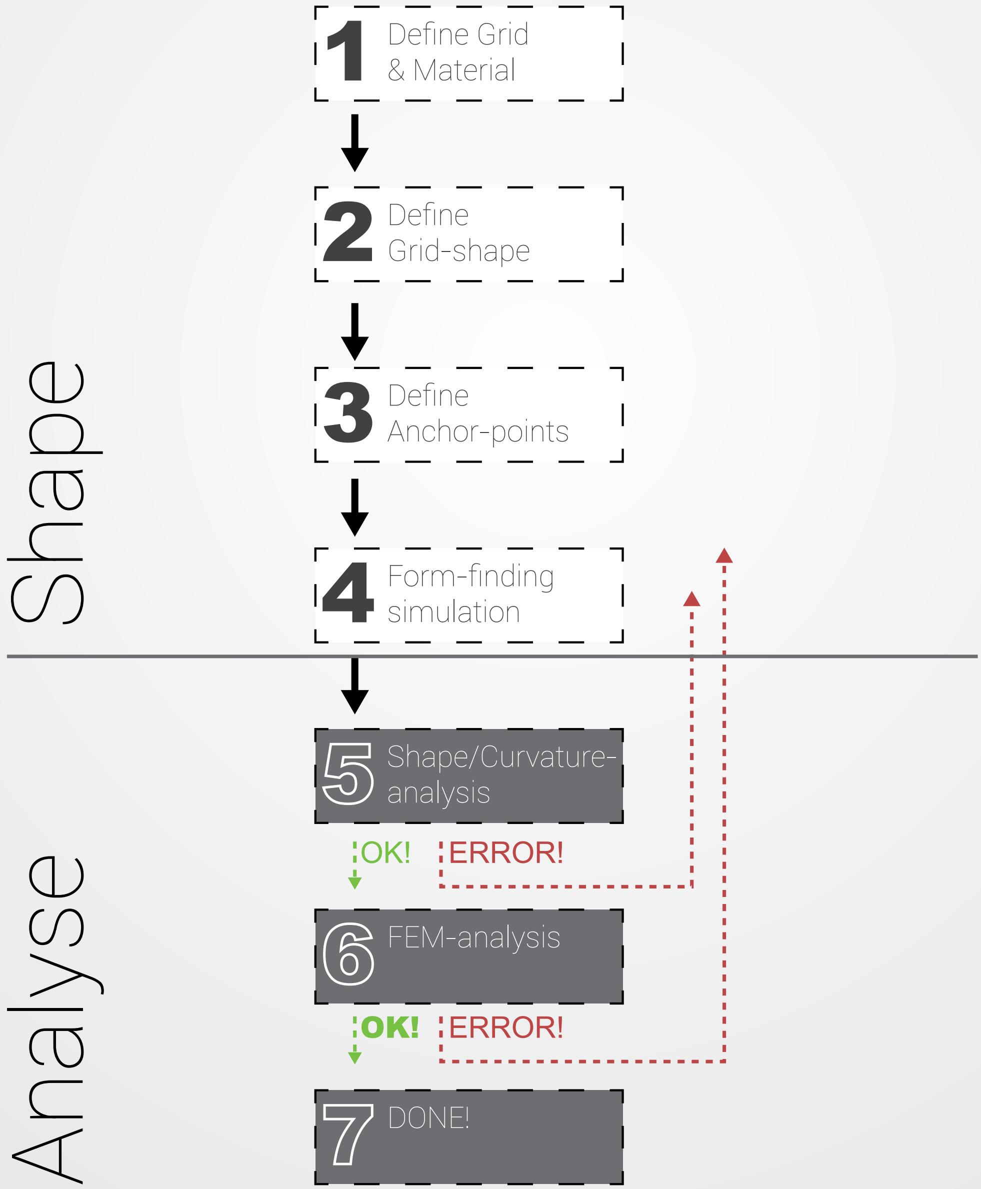
Area: 120 m^2
Price: 107250 NOK
Price pr m^2: 890 NOK

Prices collected at www.finn.no and www.futurehaller.no in march 2015.


Grid og krefter
1
2
Trimme Grid
3
Simulering
Kontroll-
panel
KREFTER
Materialgenerering
GeometriAnalyser
EXCEL-INPUT

SOFTWARE

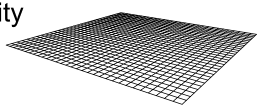
CROSS SECTION



1 Define Grid & Material

Choose a diagonal or orthogonal grid. Also choose the grid-size.

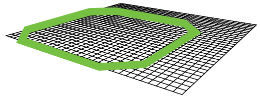
Cross -section and material-quality are also to be choosed, but can easily be changed later.



2 Define grid-shape

Draw a closed curve that defines the grid-shape.

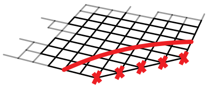
Keep it simple! It is wise to choose either 45° or 90° corners



3 Define foundations

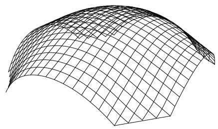
The principle is to choose wich points are to be foundations. These are then connected to a curve that the points should be attached to. This is the foundation.

The software has four foundations, but can easily be expanded



4 Form-finding

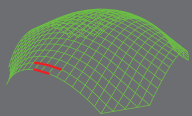
The shape is generated based on foundations and forces.
Gravity: The gravity is set up-side down.
Bending-force: Like a beam, the lines tries to resist bending.
Spring: Each segment is defined as a strong spring.



5 Shape/curvature analysis

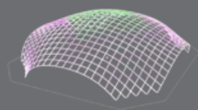
Analysis is next when shape is generated. First aestetically and functional. Graphical displays shows if some of the parts will break or some area is to0 flat.

If the shape is not approved, point 1,2 or 3 has to be adjusted.



6 FEM-analysis

A software called Karamba makes it possible to do FEM-analasys. This enables the user to add snow- and other loads on the structure. Results as deplacement and forces in the anchor-point can determine if the shape is buildable.
If the shape is not approved, point 1,2 or 3 has to be adjusted.



Software-list

The form-finding and analysis can be done in several different ways and with different softwares. Following are the softwares and purposes used in this thesis.

Rhinoceros 3D
Rhinoceros is the 3D-software that functions as a base for the geometry. This software is also used when manufacturing the elements.

Grasshopper
Grasshopper is a plugin for Rhino. This is a graphical programming language aimed for parametric modelling. Geometry is generated based on a large algorithm.

Kangaroo
Kangaroo is a plug-in for Grasshopper that enables grasshopper to add physics on the 3D. Kangaroo is responsible for the form-finding process.

Karamba
Karamba is a plug-in for Grasshopper that does analysis on a given structure. The plug-in adds material-properties and exports results like deplacement and reaction-forces.

OTHER GRIDSHELLS

Toledo 2.0, Italy

PROPERTIES

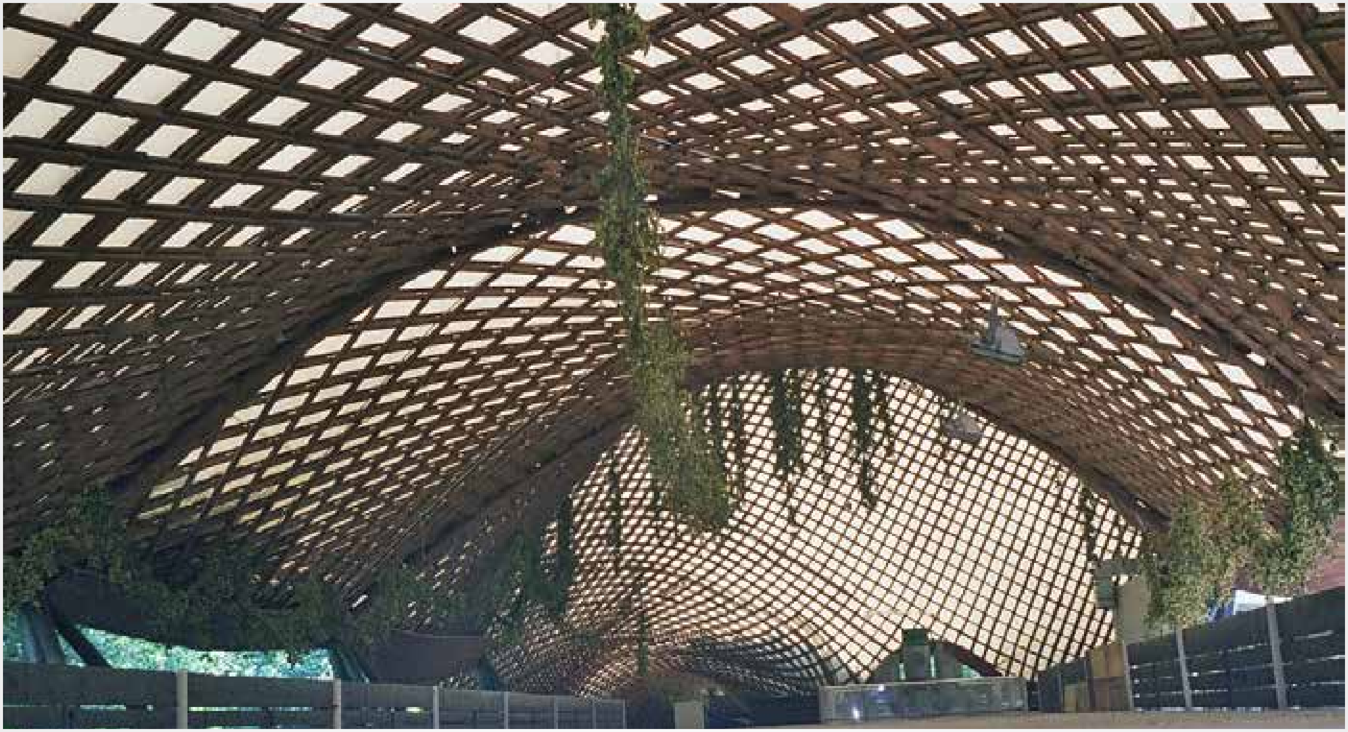
Material:	Larch	**Function:**	Eksperiment
Material-dim:	20x50mm	**Architect:**	Gridshell.it
Total span:	10x10m	**Year:**	2014
Grid-size:	500x500mm	**Weigth:**	7kg/m2
Joint	M6 Bolt+washer	**Mat.Volume:**	2m^3
Brazing	Timber		

Downland gridshell, England

PROPERTIES

Material:	Oak	**Function:**	Museum
Material-dim:	50x35mm	**Architect:**	Edward Cullian;
Total span:	50x12,5/16m	**Year:**	2002
Grid-size:	500x500,1000x1000mm	**Price:**	1097Pund/m2
Joint	4stk M8 Bolt+ brackets		
Brazing	Timber		

Mannheim Multihalle, Germany



P: Oliver Lowenstein

PROPERTIES

Material: Hemlokk Pine
Material-dim: 50x50mm
Area: 9500m²
Grid-size: 500x500mm
Joint M8 Bolt, washer
Brazing Steel-wire

Function: Swimming pool, restaurant
Architect: FreiOtto, OveArup++
Year: 1972

Savill Garden, England

P: David Baugh

PROPERTIES

Material:	Larch(Quality1&2)	**Function:**	Visitor centre
Material-dim:	80x50mm	**Architect:**	GlennHowells, BuroHappold
Total span:	2250m2		
Grid-size:	1200x1200mm	**Year:**	2005
Brazing	Plywood	**Timber length:**	20000m

Shell you later.