Authors:
Steinar Hillersøy Dyvik, John Haddal Mork
Supervisor:
Bendik Manum
Co-Supervisor:
Anders Rønnquist, Nathalie Labonnote

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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 GRID SHELL?

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 being 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 (e.g. 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.
**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 being 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
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.
8. Considering only shape, it is perfect, but it is not possible to create a gridshell like that from a flat grid.
THE SHAPE

Why good shape, why bad shape

Flat top
Is unfavorable and can lead to deformation

Tall arc
A clear shape distributes the forces correctly

EXPLANATION

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
The circle and the parabola are easy to draw, but the catenary curve is the perfect curve for even load distribution.

Wikipedia's 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.

Catenary curves work 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 absorb 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
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 itself. But the diagonal laths are much less curved.

The diagonal pattern can be useful when designing small gridshells. This because the bending capacity often is the biggest challenge.
Diagonal vs orthogonal grid

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 grid still can handle a taller top and smaller distance between anchors.
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.
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.
The kinematic construction 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 characteristics 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 anchor points is moved. See more at page 63.
Small changes - big impact

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
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.
The far best modeling method is weaving. This is only possible with materials with some friction, such as wood or plywood. This technique 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
A key element is to find the correct cross-section. Larger cross-section (height) increases the strength, but decreases the formability.
Dimensioning cross section

**EXPLANATION**

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

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

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

Different material constants

<table>
<thead>
<tr>
<th>Strength class</th>
<th>Constant</th>
<th>Cross-section (h)</th>
<th>Smallest radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>250</td>
<td>23</td>
<td>5750</td>
</tr>
<tr>
<td>C24</td>
<td>229</td>
<td>23</td>
<td>5267</td>
</tr>
<tr>
<td>C30</td>
<td>200</td>
<td>23</td>
<td>4600</td>
</tr>
<tr>
<td>D30</td>
<td>167</td>
<td>23</td>
<td>3841</td>
</tr>
<tr>
<td>D70</td>
<td>143</td>
<td>23</td>
<td>3289</td>
</tr>
<tr>
<td>Segment-lath</td>
<td>152</td>
<td>23</td>
<td>3496</td>
</tr>
</tbody>
</table>

Different cross-sections

<table>
<thead>
<tr>
<th>Strength class</th>
<th>Constant</th>
<th>Cross-section (h)</th>
<th>Smallest radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Segment-lath</td>
<td>152</td>
<td>12</td>
<td>1824</td>
</tr>
<tr>
<td>Segment-lath</td>
<td>152</td>
<td>24</td>
<td>3648</td>
</tr>
<tr>
<td>Segment-lath</td>
<td>152</td>
<td>48</td>
<td>7296</td>
</tr>
</tbody>
</table>

**EXPLANATION**

The first table exemplifies that similar cross-sections with different timber-qualities results in different radiiuses. The second table exemplifies that increasingly cross-section heights results in larger radiiuses.

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.

\[
\text{minRadius} = \text{Cross-section}(h) \times \text{Constant}
\]
Increasing radius, increasing length

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 shorter 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 construction timber

<table>
<thead>
<tr>
<th></th>
<th>Bending strength (N/mm²)</th>
<th>E-module (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C16</td>
<td>16</td>
<td>8000</td>
</tr>
<tr>
<td>C24</td>
<td>24</td>
<td>11000</td>
</tr>
<tr>
<td>C30</td>
<td>30</td>
<td>12000</td>
</tr>
<tr>
<td>D30 (oak)</td>
<td>30</td>
<td>10000</td>
</tr>
<tr>
<td>D70</td>
<td>70</td>
<td>20000</td>
</tr>
</tbody>
</table>

EXPLANATION

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

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)

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce</td>
<td>Soft, elastic, medium strength, easy to glue and paint, hard to impregnate.</td>
</tr>
<tr>
<td>Pine</td>
<td>Soft, elastic, strong, durable, easy to cut and process, hard to glue and paint, can be impregnated.</td>
</tr>
<tr>
<td>Birch</td>
<td>Ductile, elastic, low moisture resistance, easy to process,</td>
</tr>
<tr>
<td>Oak</td>
<td>Dense, heavy, hard, durable, elastic, semi-hard to process, moisture resistant</td>
</tr>
<tr>
<td>Aspen</td>
<td>Soft and loose, fluffing, moisture resistant (strongest dry), no cracking while drying</td>
</tr>
</tbody>
</table>
Wood species

Spruce

Aspen

Pine

Birch

Oak

RedOak
HOW TO BUILD
01: Precut

EXPLANATION

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

A CNC mill cuts holes and slotted holes in the laths. 38 laths require 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

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

The one cross is the base for the hole gridshell and represent the verticies in the grid.
05: Grid-assembling

EXPLANATION

Weaving the crosses repeatedly, you can create whatever grid-shape you want. The prefabricated holes maintains the correct grid-size.
How to build

06: Grid-bed

EXPLANATION

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.
How to build

07: Laying the grid

EXPLANATION

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

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.
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

EXPLANATION

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

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 that tarp will not be disrupted by the bolts.
12: Thighten the bolts

The last step is to thighten the bolts. This joins the laths and makes the structure stronger.
How to build

Others: Extending the laths

EXPLANATION

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

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

Others: Extending the laths

**EXPLANATION**

This example is from the building of the Savill garden gridshell. In order to produce knot-free, continuous laths up to 36 meters, every piece was cleaned 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 length at the building site.

P: David Baugh
How to build

Shear blocks

Plain grid has little shear stiffness

Shear blocks through weaving

Same height blocks

Taller blocks makes an I-profile-like strength

EXPLANATION

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

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
The materials listed 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
<th>Unit price</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber</td>
<td>2034 m</td>
<td>6.25 NOK</td>
<td>12 712  NOK</td>
</tr>
<tr>
<td>Bolts/Nuts</td>
<td>2825 stk</td>
<td>3.00 NOK</td>
<td>8475  NOK</td>
</tr>
<tr>
<td>Tarpolin</td>
<td>131.5 m(^2)</td>
<td>200 NOK</td>
<td>26 300  NOK</td>
</tr>
<tr>
<td>Production</td>
<td>40 t</td>
<td>750 NOK</td>
<td>30 000  NOK</td>
</tr>
<tr>
<td>Assembling</td>
<td>60 t</td>
<td>500 NOK</td>
<td>30 000  NOK</td>
</tr>
</tbody>
</table>

TOTAL: ≈108 000 NOK

Price pr m\(^2\): ≈820 NOK
OTHER WAYS TO MAKE SPACE

Area: 90 m²
Price: 75000 NOK
Price pr m²: 830 NOK

Area: 120 m²
Price: 107250 NOK
Price pr m²: 890 NOK

Prices collected at www.finn.no and www.futurehaller.no in March 2015.
SOFTWARE
1. Define Grid & Material
2. Define Grid-shape
3. Define Anchor-points
4. Form-finding simulation
5. Shape/Curvature-analysis

OK!  ERROR!

OK!  ERROR!

DONE!
1 Define Grid & Material
Choose a diagonal or orthogonal grid. Also choose the grid-size.
Cross-section and material-quality are also to be chosen, 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 which 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 too 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-analaysys. 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 displacement and reaction-forces.
OTHER GRID SHELLS
**Toledo 2.0, Italy**

<table>
<thead>
<tr>
<th><strong>Properties</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td>Larch</td>
</tr>
<tr>
<td><strong>Material-dim:</strong></td>
<td>20x50mm</td>
</tr>
<tr>
<td><strong>Total span:</strong></td>
<td>10x10m</td>
</tr>
<tr>
<td><strong>Grid-size:</strong></td>
<td>500x500mm</td>
</tr>
<tr>
<td><strong>Joint</strong></td>
<td>M6 Bolt+washer</td>
</tr>
<tr>
<td><strong>Brazing</strong></td>
<td>Timber</td>
</tr>
<tr>
<td><strong>Function</strong></td>
<td>Eksperiment</td>
</tr>
<tr>
<td><strong>Architect</strong></td>
<td>Gridshell.it</td>
</tr>
<tr>
<td><strong>Year</strong></td>
<td>2014</td>
</tr>
<tr>
<td><strong>Weigth</strong></td>
<td>7kg/m2</td>
</tr>
<tr>
<td><strong>Mat.Volume</strong></td>
<td>2m³</td>
</tr>
</tbody>
</table>
Downland gridshell, England

**PROPERTIES**

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

**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
OTHER GRID SHELLS

Savill Garden, England

**Properties**

**Material:** Larch (Quality 1 & 2)  
**Material-dim:** 80x50mm  
**Total span:** 2250m²  
**Grid-size:** 1200x1200mm  
**Brazing**  
**Function:** Visitor centre  
**Architect:** Glenn Howells, Buro Happold  
**Year:** 2005  
**Timber length:** 20000m
Shell you later.