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Modular kinematic timber gridshell; a simple scheme for constructing advanced shapes

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Abstract

This paper explains the construction scheme of a modular post formed gridshell. The scheme uses timber modules connecting laths of 900 mm length into a 2-layer module. The scheme and the module are designed to efficiently handle both Form Finding, Fabrication and Raising, and they are tested through the construction of a full scale pavilion in Trondheim, Norway.

Keywords: Timber post formed Gridshell, Timber Structure, Digital Form Finding, Full scale prototype, Segment Lath

1. Introduction

Kinematic Gridshells are elegant and light structures that can create complex shapes by simple means. Gridshell structures have been constructed in various forms from the beginning in Vyksa [1], to Edmund Happold's experiments with lattice roofs in the 1960s [2] and Frei Otto's design of Mannheim Multihalle [3] in 1975. The last decades in United Kingdom, timber gridshells returned in the form of the Weald and Downland Museum (2002), Chiddingstone Orangery (2004) and the Savill Building (2006). More recently Sergio Pone and Sofia Colabella with their group: gridshell.it [4], performed several gridshell experiments on a smaller scale, and set the agenda for the development.

While buildings with simple shapes easily can be constructed by simple, repetitive procedures, advanced shapes often demand complex construction schemes. With new tools for both designing and manufacturing, the construction of gridshells have again resurrected. The work of Pone and Colabella [5] has shown the potential of gridshells with the construction of several structures the last decade. The development at the same time of the modelling add-in: Kangaroo [6] from Daniel Piker has been crucial for performing any form finding process.

However, the previously cited examples have all shown common issues. Among others, Naicu [7] described the construction process as more complicated and more time consuming than necessary. Issues are found in the three following phases: 1) Form Finding, 2) Fabrication and 3) Raising

This paper describes a kinematic gridshell construction scheme, which in itself simplifying the whole process. The present scheme uses both digital form finding with Grasshopper [8] and manufacturing with CNC milling. The scheme is also demonstrated through the construction of a 10x10x4m pavilion in Trondheim, Norway, in 2015.

2. The gridshell in Trondheim

The Trondheim pavilion [Fig.1] was built as part of a master thesis in architecture at the Norwegian University of Science and Technology, NTNU. The entire manufacturing and building took ten days and was performed by only two persons. The shell has a setup of 28x28 nodes of a quadratic grid with center-to-center distance of 500 mm. It is a flat grid of 13.5 m from foundation point to foundation point, with chamfered edges of 6 nodes width [Fig.2].

Figure 1
Photo of the gridshell pavilion built in Trondheim.

The final shape has an 11.2 m outline, while the foundation edges are moved 2.12 m towards the centre. This created openings of 5.4 m and heights of 2 m in the openings and 4.1 m in the centre. The construction stood for 6 months, and was tested for structural performance before disassembly. The structural performance test is described in another publication [9].

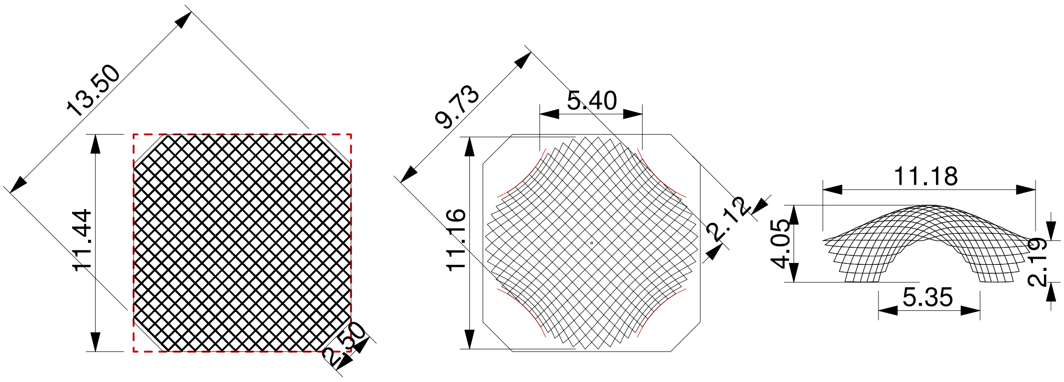

Figure 2
Dimensions of the planned gridshell pavilion built in Trondheim. The dimensions varied slightly in the final pavilion. Left: Size of the flat grid. Right: Sizes of the raised construction.

3 Construction scheme

The scheme described in [Fig.3] is greatly inspired by the work of Pone and Colabella and the Trondheim pavilion is similar in both scale and techniques to many of their projects, also regarding the gridshell form finding tool (gfft) [5].
The construction scheme is divided into three parts; form finding, fabrication and raising. The form finding can be done without having decided construction principles, thus taking this decision can feed back information to the form finding. Through the explanation of the scheme, the aim is to highlight the improvements made in both form finding, fabrication and raising.

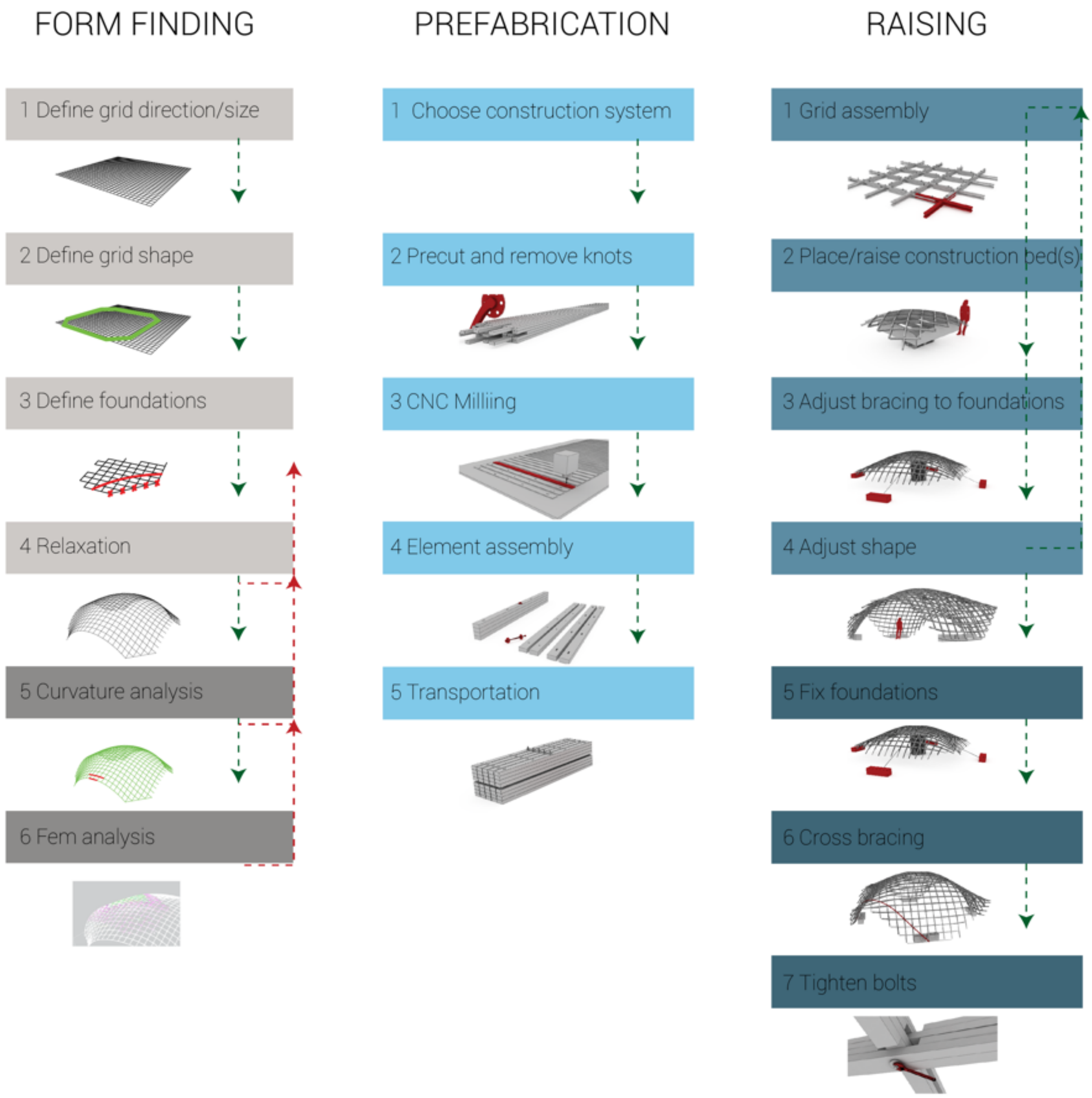

Figure 3
The three parts of the construction scheme are described in this paper

3.1 Form finding

The shape is found by using dynamic relaxation with Grasshopper and Kangaroo. The grasshopper code, from now on referred to as "the code", includes structural analyses taking into account material properties and curvature considerations. The form finding setup is described with the following steps:

1. Preparation phase
    a. Create a grid with the desired grid direction (orthogonal or diagonal) and grid size [Fig. 4]. The number of nodes is picked approximately to give an outline for the next step.
    b. Define the outer shape of the flat grid by drawing a curve with the desired shape within the nodes. The code recognizes the nodes inside the curve, and creates the grid according to them.
    c. Extract the outer points from the grid, and define a selection of them as anchor points for the construction. This corresponds to the actual foundation points.
    d. Draw the anchor curve in rhino and connect it to the code. The anchor points will be pulled towards the anchor curve later. In the double symmetric alternative, one anchor curve is drawn and the rest are mirrored in position. A curved anchor curve gives better performance compared to a straight anchor curve.
2. Form finding phase [Fig. 5]. The code is designed with four important physical conditions:
    a. An inverted gravity force pushes the grid upwards.
    b. The bending resistance of the laths is modelled as a force trying to keep them flat.
    c. Laths are defined as strong springs that are allowed to stretch only a fraction of their length.
    d. The anchor points are assigned a pull force pulling them towards the anchor curves.
3. Form adjustment
    a. The shape can be modified by moving and adjusting the anchor curve.
    b. The code gives feedback on the curvature of the shell. It is possible to assign a timber type and quality so that the corresponding minimum curvature is checked. The software code colorizes the laths curved over their capacity.
    c. The code is also connected to Karamba for structural analysis [10] [Fig. 6].

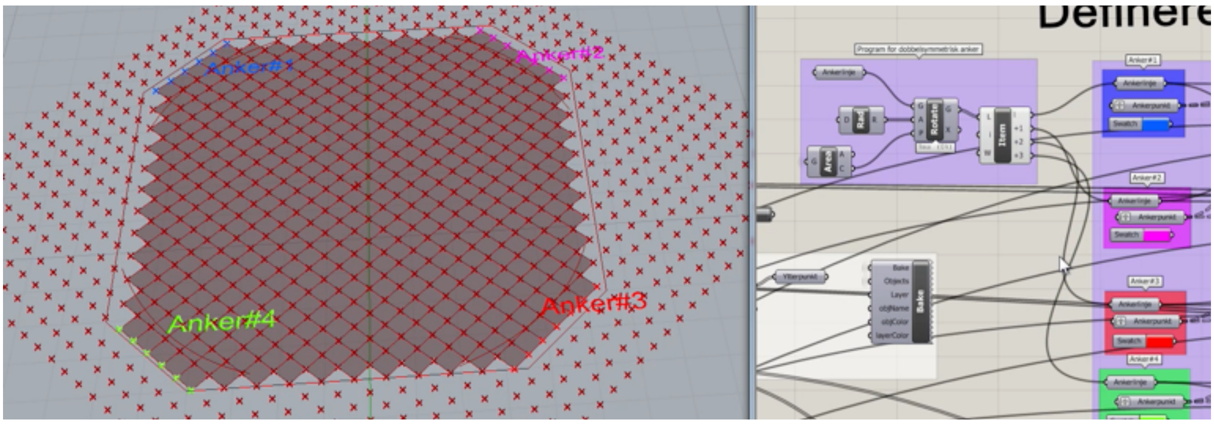

Figure 4
The form finding starts by deciding grid size and direction, and by drawing an approximate outline of the flat grid. The anchor points are then extracted and connected to the code.

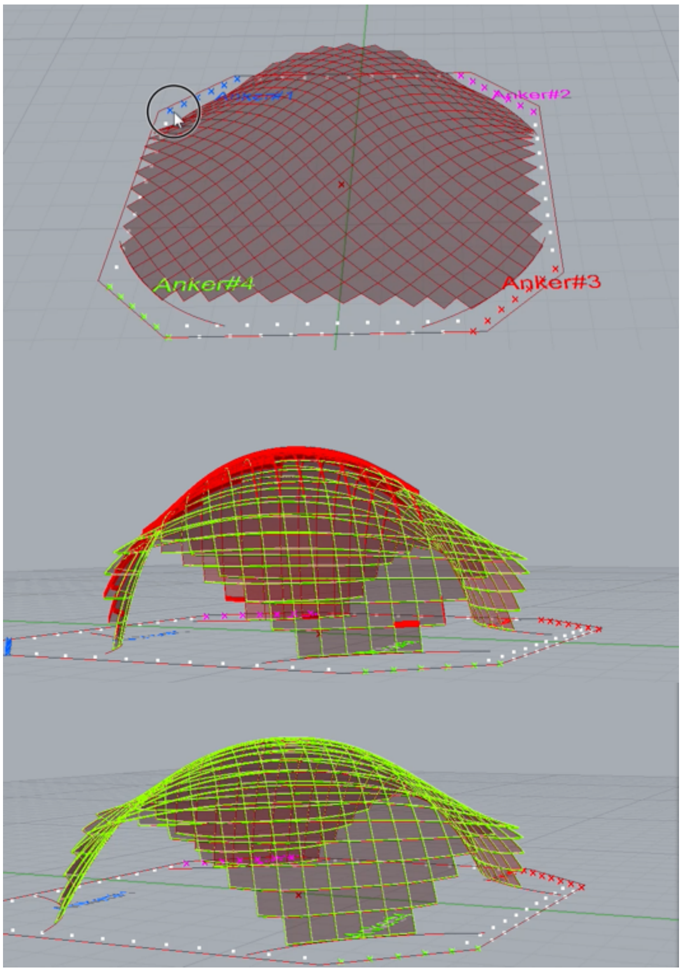

Figure 5
Further steps of the form finding. With a minimum curvature analysis based on material quality, the model can check whether it is possible to construct the found shape.

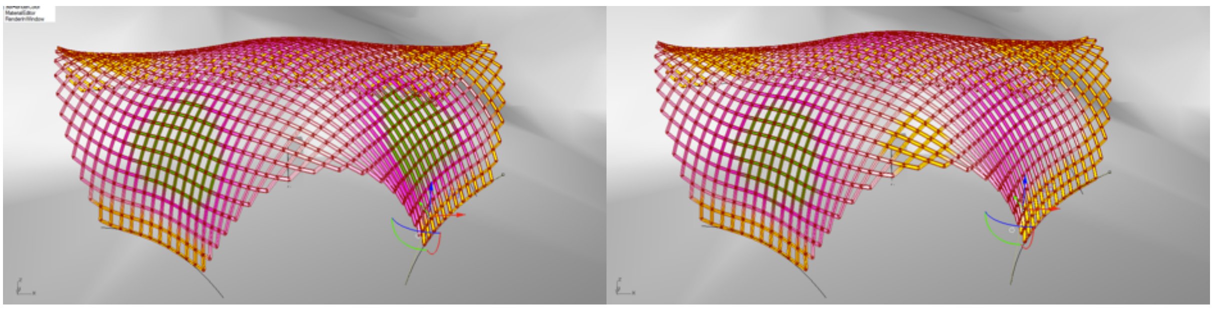

Figure 6
Structural performance testing with Karamba. The image to the right has a slightly change in the foundation curve.

3.2 Construction method - The Segment Lath

A crucial development for this scheme is the design of the Segment Lath [Fig. 7]. Instead of finger joining, lap joining or irregular extension systems, the exception has been made the rule. The grid is constructed with a two-layer module of four 900 mm laths. Each lath has five milled holes, one in the centre for the node, and two on each side for weaving. Since the module only consists of a node and up to four connectors, the Segment Lath can adapt to any grid size. The Segment Lath solution exhibits the following features:

1. The Segment Lath solves the issue of knot removal [Fig. 8]. The 900 mm pieces can be cut manually for avoiding knots, or be pre-cut and then sorted for a faster removal of knots process. Material waste due to knot removal process is higher with larger grid sizes.
2. Since overlapping is a rule, acquiring the correct length of the laths [Fig. 7] is never an issue with the Segment Lath solution. With other solutions, timber laths longer than 4m are usually hard to acquire.
3. The Segment Lath solution includes by default shear blocks due to overlapping [Fig. 9]. For other solutions, shear blocks need usually to be added in between two layers in order to increase the total moment of inertia and thereby the bending stiffness. With the Segment Lath solution, the height of the shear block depends on the actual lath heights [Fig.10], but the length can in theory be optimized for the grid to save material and weight.
4. The centre hole in each piece is circular, and the side holes are either circular or slotted. The top and bottom layers have slotted holes, allowing free sliding relative to the central layer.
5. Cross bracing is not included in the Segment Lath solution. In this study the cross bracing is handled in an outer layer.
6. Transportation of the grid is efficient, as the modules gets compact once folded. In the Trondheim pavilion, the whole grid needed only two Euro-pallets, i.e. about $2m^3$, for transport from workshop to the site [Fig. 11].

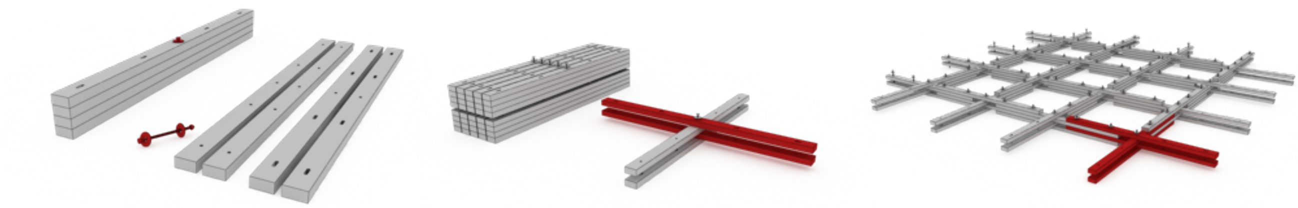

Figure 7
The Segment Lath. From module to assembly.

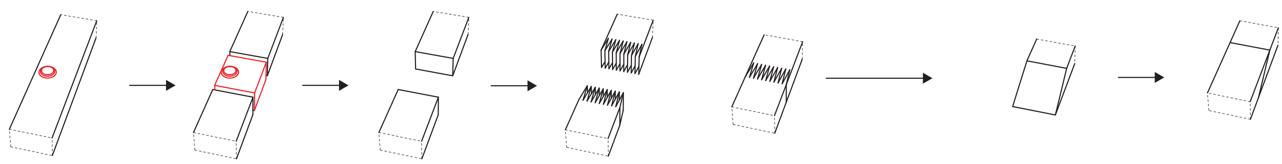

Figure 8
Knot removal in Saville building. The Segment Lath gives another solution to these issues.
Top: Knots were removed, and finger joint up to 6 meter lengths.
Bottom: In this case they were also extended from 6 to 36 meters using lap-joints.

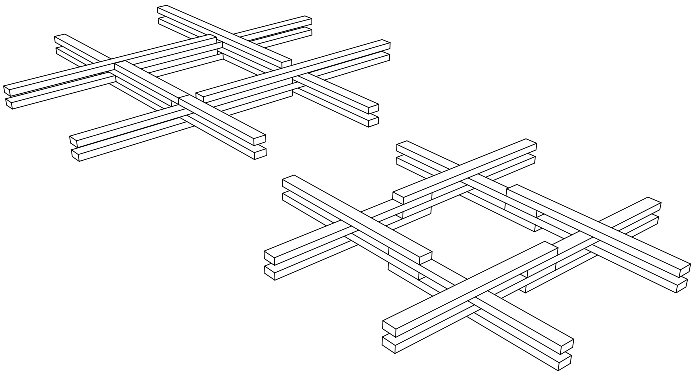

Figure 9
The overlap in the Segment Lath has the same function as the shear blocks. Same grid size can be archived with different overlaps.

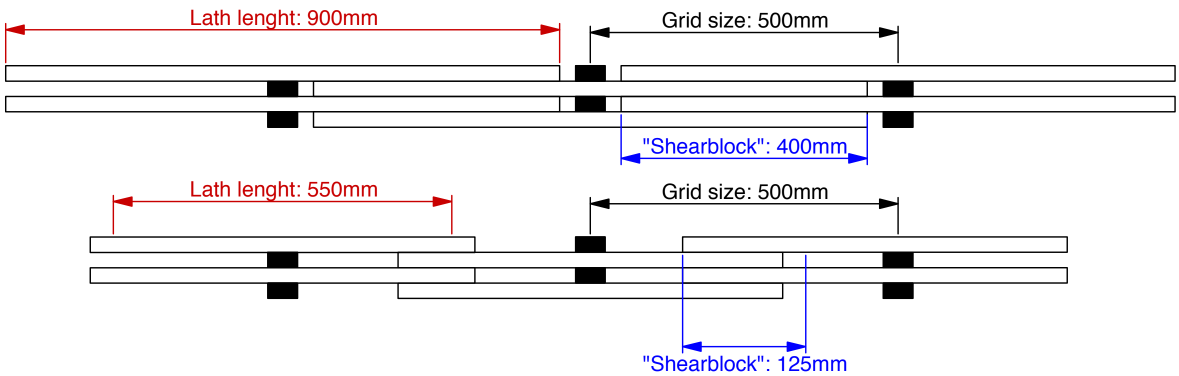

Figure 10
Top: Maximum lath length for the chosen grid size, as in the Trondheim pavilion.
Bottom: Different lath length, but same grid size.

Figure 11
The Segment Lath makes transportation very compact. This picture shows 50% of the modules in the Trondheim pavilion.

3.3 Raising

The erection of the Trondheim pavilion was done by two persons. For larger scale projects, the use of more workers may lead to even shorter erection times. The erection process exhibits the following steps:

1. The site is prepared and foundations placed in their correct positions. The location of the foundations and the grid-bed are the only measures needed to start the raising of the structure. To get a precise form it is also necessary to measure reference positions, like the height on the top and next to the entrances
2. A grid-bed [Fig.12] is made to guide the construction in place. The grid-bed has the same shape as the final grid at the same position. In the Trondheim pavilion, it was placed in the centre [Fig. 13]. This method is also applicable to larger gridshells.
3. The grid-bed is placed on a Euro-pallets and continuously raised throughout the construction process. A step-by-step lifting is performed by adding one pallet for each step. In the Trondheim pavilion, a manual pallet jack was used [Fig. 14].
4. The manufactured modules are assembled into a grid of a manageable size, slightly larger than the grid-bed. This initial grid is then placed in position on top of the grid-bed.
5. More Segment Lath elements are added sequentially to the grid, evenly around the centre [Fig. 15]. Because the added elements contribute only to a slight weight increase, the shell does not lose balance under assembly. The shell is connected to the foundations with straps during the raising in order to secure stability.

Figure 12
The shape of the grid-bed is taken directly from the 3D model, and cut to fit the final shape.

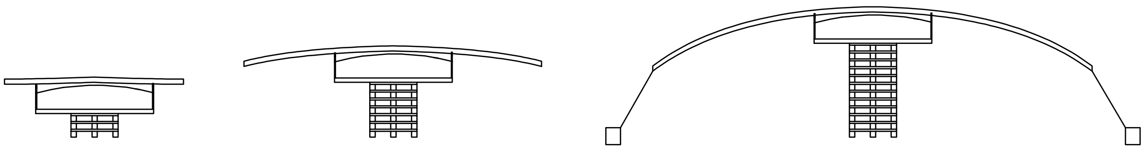

Figure 13
Adding pallets raises the shell evenly and helps keeping a good working height. Gravity participates to shaping the shell gradually as more weight is added. At a point, temporary bracing is added to keep the structure mode in balance.

Figure 14
The pallets can be lifted with a manual pallet jack, but in larger projects a fork lift is more relevant.

Figure 15
Connecting a new module done in a good working height. Too much tension can make the connecting more difficult.

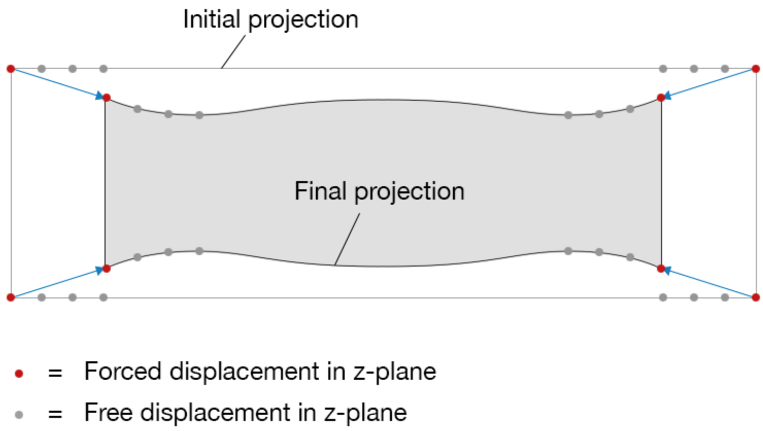

Figure 16
The curved shape of the anchor curve found using Abaqus.

4. Discussion

- The geometry of the anchor-curves is critical to reach a good final shape. Straight lines seem to be the worst alternative. A form-finding test performed in the commercially available finite element software Abaqus, with anchors free in xy-plane also resulted in a curved shape [Fig. 16].

- A notable found using Karamba, is how the structural performance of the shape is significantly improved by fine-tuning the geometry of the foundations [Fig.5]. This is considered as very useful for further optimization processes.

- Further studies are needed in order to conclude on the effect of overlapping distance / length of shear blocks on the structural performance.

5. Conclusions

- This paper highlights the possibilities of a modular kinematic gridshell construction scheme. The Segment Lath solution provided substantial improvements to many known challenges of kinematic gridshells, among others: knot removal, shear blocks, fabrication and transportability.

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References

[1] Beckh M, Barthel R. The first doubly curved gridshell structure-shukhovs buildings for the plate rolling workshop in Vyksa. In: Proceedings of the third international congress on construction history. 2009. p. 159–66.

[2] Happold E, Liddell W. Timber lattice roof for the Mannheim Bundesgartenschau. Struct Eng. 1975;53(3):99–135.

[3] Liddell, I., Frei Otto and the Development of Gridshells. Case Studies in Structural Engineering, 2015.

[4] Pone S, Colabella S, gridshell.it structures [Internet] Available from: www.gridshell.it

[5] Pone S, Colabella S, D'Amico B, Lance D, Fiore A, Parenti B. Timber post-formed gridshell: Digital form-finding/drawing and building tool. In: Proc of the IASS Symposium, Wroclaw, Poland. 2013. 6

[6] Piker D. Kangaroo: form finding with computational physics. Archit Des. 2013;83(2):136

[7] Naicu D, Harris R, Williams C. Timber gridshells: Design methods and their application to a temporary pavilion. In: World Conference on Timber Engineering (WCTE) 2014. University of Bath; 2014.

[8] McNeel R. Grasshopper3d [Internet]. Available from: www.grasshopper3d.com

[9] Labonnote N, Mork JH, Dyvik SH, Nilsen M. Rønnquist A, Manum B, Experimental and numerical study of the structural performance of a timber gridshell, accepted in World Conference on Timber Engineering, August 22-25 2016, Vienna, Austria

[10] Presinge C. Karamba 3d [Internet]. Available from: www.karamba3d.com