INTRODUCING THE SEGMENT LATH –A SIMPLIFIED MODULAR TIMBER GRIDSHELL BUILT IN TRONDHEIM NORWAY

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INTRODUCING THE SEGMENT LATH - A SIMPLIFIED MODULAR TIMBER GRIDSHELL BUILT IN TRONDHEIM NORWAY

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ABSTRACT: The paper introduces a kinematic gridshell principle built with the smallest possible module. The module consists of only two laths providing one node and the four connectors to adjacent nodes. The solution is named the segment lath and the result is a system able to construct any quadratic grid shape using only one module type. Among other assets, the system includes the function usually handled by additional shear blocks, it enables simplified manufacturing, compact transportation, fast construction and efficient use of materials. Further, the paper describes the process of designing and building a 10 meter full scale segment lath gridshell in Trondheim, Norway.

KEYWORDS: Kinematic timber gridshell, segment lath, simplified modular system, full scale prototype, compact transportation

1 INTRODUCTION

The elegance of a gridshell lies in its complex shape built up by simple elements. A kinematic gridshell, originally called timber lattice roof, is defined as a flat squared lattice that is lifted (or lowered) into a doubly curved shape[1]. In principle, the same connection detail can be applied in all nodes except for the edges. In addition, the distance between the nodes are uniform. Natural limitations determine the length of laths. A high-quality timber-lath, off the shelf, can be up to six meters, but depending on chosen specie and irregularities, most laths must be trimmed to achieve the needed quality. The laths are then joined by various techniques to achieve the required lengths of the laths in the complete shell.

Gridshells have been developed since 1890's by the pioneer Vladimir Shukhov[2], but Frei Otto together with Edmund Happold and Ian Liddel is a main reference regarding the development of the timber based kinematic gridshell. In 1975, they constructed and built the Mannheim Multihalle, a 7400 m^2 gridshell that spans up to 85 m. Their solution was a double layer configuration using 50x50mm hemlock laths. Extension of laths were done by finger joints.

Later, the Weald & Downland Gridshell and Savill Garden were built, both engineered by Buro Happold[3]. While shape, grid-size, material and program differs, both projects uses continuous laths and the same extension strategy: off-site finger joint laths to 6 meter lengths, and then on site scarf-jointing to full-lengths on site.

Despite gridshell's simplicity and fairly low price compared to other doubled curved structures, kinematic gridshells are still not widespread. One reason is likely to be high complexity in design process. However, new digital form-finding tools, such as Grasshopper 3D[4] , Kangaroo Physics[5] and Karamba 3D[6], has potentially enabled a new era in the development of kinematic gridshells.

Currently, different research groups are further developing the concept. Gregory Charles Quinn and team has elaborated the potential using pneumatic false work as erection-method[7]. Gridshell.it, led by Sergio Pone, has developed and built different prototypes and medium-scaled structures. Further-more they have developed their Gridshell Form finding tool (GFFT)[8]. Their grid-system is similar to Mannheim Multihalle, but differs in extension-principle. Instead of using finger-joints, the system is divided into 4x4 grid that are bypass-connected. See figure 1. The small geometric change both modularize the system and makes the manufacturing less demanding. Gridshell.it`s solution is a large step towards a simplified gridshell.

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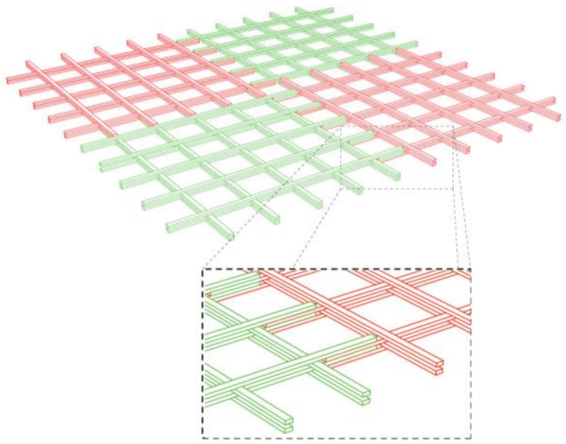

Figure 1: *Gridshell.it`s modular system.*

However, by this principle, the joints between the modules visually appear as disturbing exceptions to the rule. Together with the variations of the module needed for adapting the modules to the shape of the complete shell, the modular system weakens the architectural clarity that at best characterises a gridshell. This paper investigates the potential of an even simpler and more universal modular system and is tested through a full-scale pavilion. The structure is shown in figure 2 and 3. The solution is named the segment-lath.

Figure 2: *The pavilion built in Trondheim*

Figure 3 *The structure and the belonging site*

2 THE SEGMENT LATH SOLUTION

2.1 Schematic Concept

This is a novel approach to kinematic gridshells utilizing the advantage of a simplified modular system parallel to that of binary numbers. An integer can be expressed by decimal or binary numbers. The decimal numeral system needs ten symbols; 0,1,2...9 to express all possible integers whereas the binary number manage the same by two symbols; 0 and 1. Similarly, an arbitrary grid can be described by many types of large elements or by fewer, smaller elements. A grid could essentially be expressed with node coordinates and the relation to adjacent nodes. This is also the principle for the modular concept presented here; a module as simple as two segmented laths, connected in the centre.

Figure 4 shows the module, Figure 5 how it is assembled, while Figure 6 compares continuous laths against segmented laths. This simple example illustrates how four different elements are required as continuous laths whereas one kind of the segment lath-module is sufficient. A more complex shape would demand further additional continuous laths while only one segment module is needed also this time.

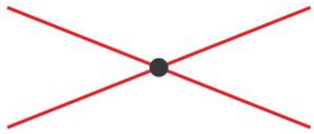

Figure 4 *The smallest possible module, containing only two laths and a node.*

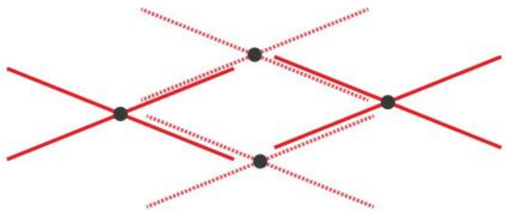

Figure 5: *How the modules relates to each other.*

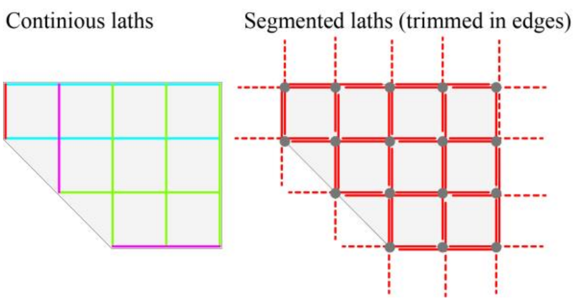

Figure 6: *Same grid shape constructed by continuous and segmented laths, respectively. Colours represent different lengths required.*

2.2 Materializing the concept

A double layered configuration of the module turned out to be advantageous for several reasons. One layer is here defined as one complete representation of the grid (The thickness of the gridshell is four laths, but still has to layers). However, both a single-layer and a multilayer system is possible. Each module is bypass connected, creating an almost solid structure and reducing the need of additionally shear-blocks. By this, the extensions becomes the rule rather than an exception from the rule. The bypass-connection(3) and other extension tecniques are illustrated in Figure 7.

Figure 7: *Comparison of extension techniques. (1) Finger jointing, used in Mannheim Multihalle, Weald & Downland and Savill Garden (2) Scarf jointing, used in Weald & Downland and Savill Garden. (3) Bypass jointing, used in segment lath and gridshell.it`s pavilions (4) Lap-jointing, used to repair broken laths in Mannheim Multihalle*

One bolt and four laths constitute the module and includes a node and the halves of four bypass-connections towards adjacent nodes. The module is extremely compact regarding transportation. See figure 8. By rotating two laths 90°, the module is ready for assembly, see figure 9. The modules are “weaved together” and joined as shown in figure 10. As previously mentioned, the simple modules can replicate any kind of quadratic grid shapes. Figure 11 shows an arbitrary grid.

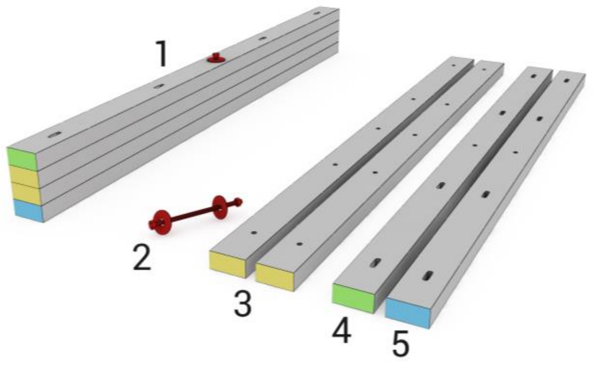

Figure 8: *Components and assembled segment module. 1) Assembly, 2) 110mm bolt/washer/nut. 3) Centre laths, with round holes. 4) Top lath with slotted holes. 5) Bottom lath with slotted holes. The coloured cross sections explain assembly order.*

Figure 9: To the left: Transport friendly setup. To the right: Assembly ready module

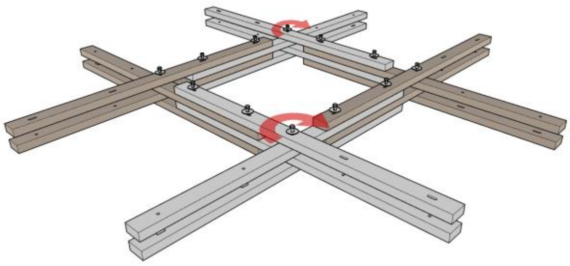

Figure 10*: Four modules connected. The grey ones are turned 90° related to the other two, creating a wowed pattern. The bypass-joints becomes the rule rather than an exception from the rule.*

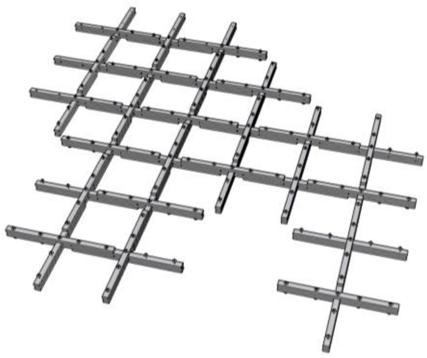

Figure 11: *An arbitrary grid constructed by the module*

For the Trondheim Pavilion, a 500x500mm grid was chosen. The size of the laths are 23mm x 48 mm, rendering a total height of 92mm. The laths are 900 mm long, making the biggest possible overlap without making the laths collide. The choice of the large overlap is twofold: First, the large overlap replaces the shear-blocks. Second, the distance between the bolts connecting the overlap is crucial to make a connection that provide continuous rather than hinged structural elements. The overlap is shown in Figure 10.

Similar to other kinematic gridshell concepts, the nodes must allow for in-plane rotation. This is solved using pinned nodes. Additionally, when applying a double-layer system, the top and bottom lath must slide relative to each other. This due to different lath curvature in the final shape. Commonly, this problem is solved by applying a pinned node with slotted holes in the top and bottom lath. The centric laths has round holes. However, the node is a vulnerable part of the grid, and because the segment laths are not continuous, it is possible and favourable to move the slotted holes to the bypass connection. By this principle, the lengths along the centre of the laths are fixed, whereas the lengths along the top and bottom laths change in accordance with the curvature of the shell. Compared to conventional concepts using slotted connections, the segment solution can utilize shorter lengths of the slotted holes. The needed slot length is dependent on the length between the end nodes on the lath. See figure 12 for graphic explanation.

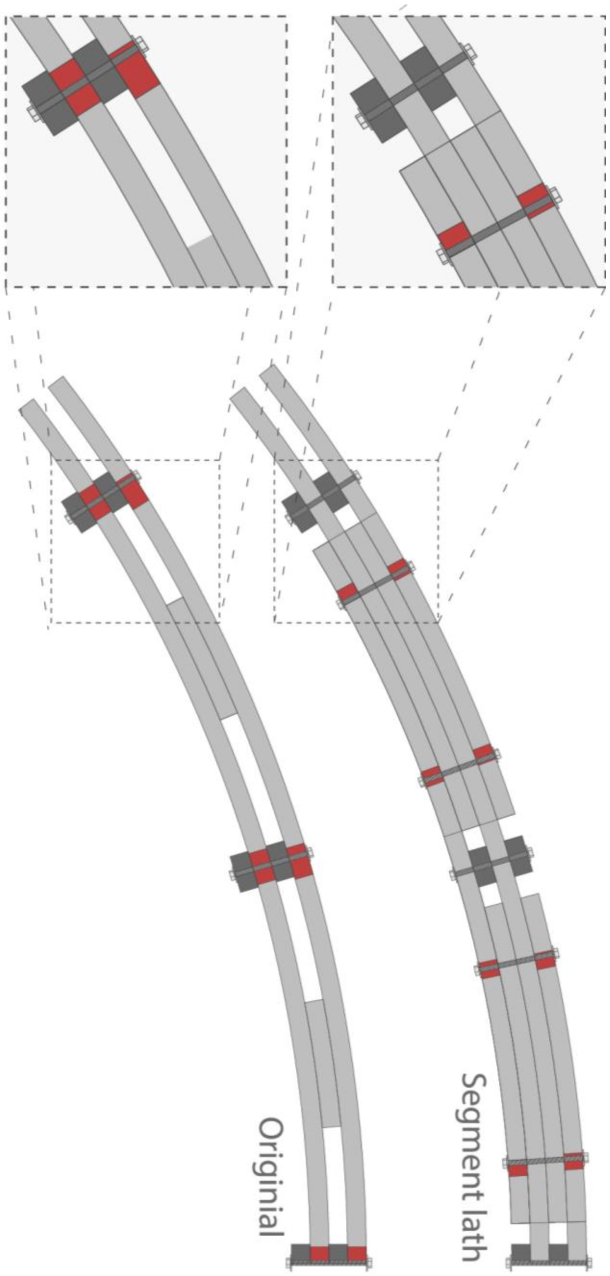

Figure 12: *Original solution (like Mannheim Multihalle) and Segment lath to the right. Due to different length between end nodes on each lath, different lengths of the slots (coloured red) are needed. With the illustrated curvature, original solution demands 40 mm while segment lath demands only 20 mm.*

3 MATERIAL

Spruce and pine are the mostly used species in Norway. Due to price and local availability, spruce was chosen. Contrary to oak, larch and other frequently used gridshell materials, spruce have a large amount of knots, which significantly weakens the structural properties. A 5 meter lath without any knots is hard to find. Thus, applying spruce would be an unfortunate choice if using conventional solution with continuous laths. However, the use of the segment solution made it easy to extract 900 mm knot free segments, leaving minimal waste. The cutting process is shown in figure 13.

Figure 13: *Cutting the segment. The pile on the right shows the lengths of the waste.*

The shape of the shell is determined by many parameters, including the lath`s maximum bending capacity. A relation between minimum radius and cross-section height can be derived[9]. See equation 1.
Through a series of bending tests, a constant was also extracted for the chosen material. To check the buildability of the structure, this constant were implemented in the algorithm. Table 1 describes different standardized qualities (from EN 338), including the physical tested timber.

$$Constant = \frac{minRadius}{CrossectionHeight} \qquad (1)$$

Standards	Constant	Cross section height	Smallest radius
C16	250	23	5759
C24	229	23	5270
C30	200	23	4600
D30	167	23	3840
D70	143	23	3290
Tested lath	152	23	3500

Table 1: *Shows the relationship between cross section height and smallest radius*

4 MANUFACTURING

The segment lath consist only two different elements: The top/bottom lath and the centre lath, making the manufacturing process extremely simple. It consists merely of drilling five holes in each lath. The top/bottom laths getting slotted holes except in the centre. However, the precision of the holes are very important, and were for the Trondheim gridshell manufactured by a CNC-router. For large scale-manufacturing, a customized jig should be considered. In this case, the 2400x1200 Multicam 3000 router handled 38 laths in one run. Including on/off loading, one run was done in 15 minutes, implying one lath manufactured in less than 30 seconds. Jig and router seen in Figure 14 and ½ of the complete gridshell can be seen in Figure 15.

Figure 14: *The CNC-router mills five holes in each lath.*

Figure 15: *½ of the complete gridshell stacked on one pallet*

5 DIGITAL FORMFINDING

While Frei Otto used physical hanging chain models to determine shape, most form finding are now done digitally. A setup combining Rhinoceros, Grasshopper 3D and Kangaroo Physics makes it possible to simulate hanging chain structures. Kangaroo software uses dynamic relaxation algorithm to trace the motion of the structure through time under applied load. To determine if a suitable shape was found, several tests were performed. The most important one visualizes areas that have too small radiuses. The workflow is greatly inspired by Gridshell.it`s GFFT tool[8].

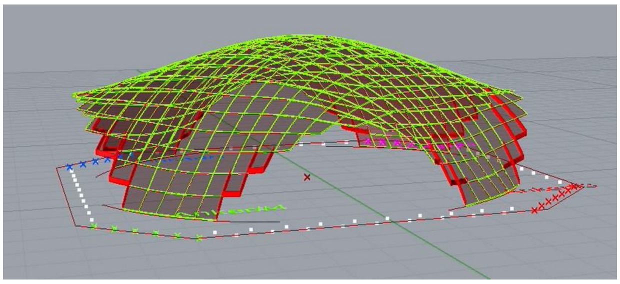

Figure 16: *Curvature test. Red laths have too small radius, green laths ok. Analysis is performed using equation 1.*

Additionally, Karamba 3D, a finite element analysis tool for Grasshopper, were used to estimate utilizations and displacements. The tool made it easy to rapidly refine the shape, searching the smallest possible moment-forces in the members as well as minimum deflections. Figure 17 shows the chosen framework.

Again, since the module is simplified, so are also the output from the design. A simple grid-scheme, key coordinates and number of modules are all that is needed to replicate the grid and final shape.

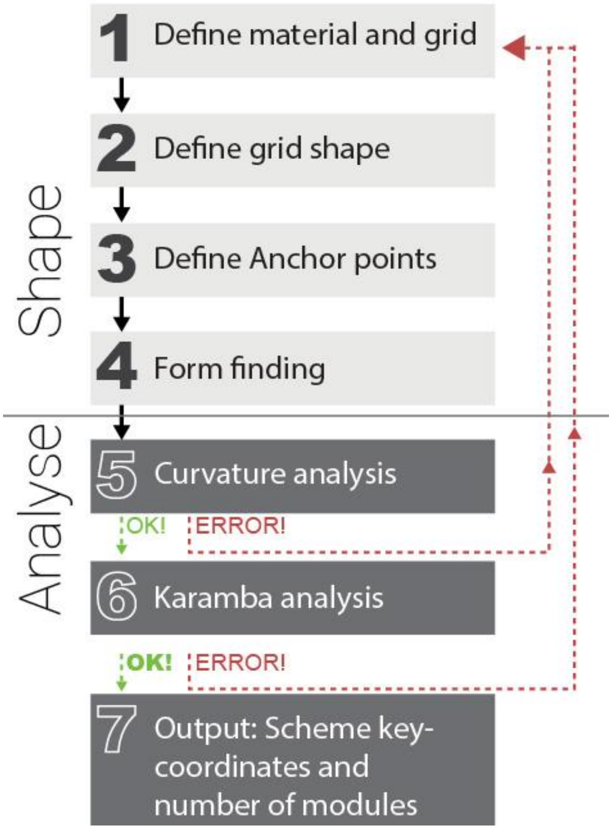

Figure 17: *The framework developed in Grasshopper 3D*

6 CONSTRUCTING A FULL SCALE PAVILION

A park in Trondheim, Norway, was chosen as prototype location. A low stone wall and broadleaf trees surround an open area that fitted the pavilion structure. The layout is a quadratic grid with 27 cells (13.5 meters) in each direction, but trimmed at each corner. The setup is shown in figure 18.

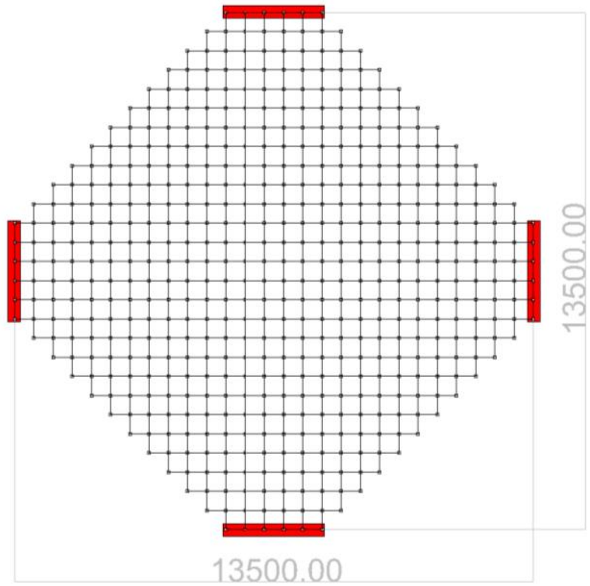

Figure 18: *Scheme of chosen setup. Red rectangle highlights the foundation points.*

The four shortest sides of the octagon are the foundation-edges. When erected, the structure is approximately 9.5 meters wide and 4 meters tall. 520 modules, or 2080 segments, are used to build the whole structure, which is a total of 2.06 m^3 timber.

6.1 Building process

The structure was built by only two persons, using a push-up technique. On site erection was conducted using a centric tower made out of pallets. The tower was then incrementally elevated by adding pallets at the bottom. On top, a 2400x2400mm plywood frame was installed to secure even load distribution on the laths during erection. The grid was assembled by starting with the centre module, leaving the bolts un-tightened. By always adding evenly around the centre, the pallet tower was always kept in balance. The incremental lifting technique made it possible to always assemble modules on ground, keeping an ergonomic and efficient working position.

Figure 19: *From the erection process. The pallet tower in the centre is incrementally heightened. The border was always approximately 1200 mm from ground level*

The anchor-points were pulled towards four already positioned foundations using cargo straps. The last part of the lifting process was conducted solely by pulling the anchor points, ensuring a controlled decentring from the tower. When shape was satisfying, the bolts were tightened and bracing added on top.
Building the structure took about 10 days, but can be significantly rationalized for further structures.

A problem is that elements might break during the erection process. Local stresses become too big on one element. Traditionally this has been tricky to fix properly, the continuous laths are very difficult to remove. Mannheim Multihalle uses a lap joint to repair these fractures.
An advantageous benefit from the segment lath is the ability to easily replace broken elements. The short length makes it possible to replace an entire module by removing lath by lath.

Figure 20: *Fully erected pavilion viewed from one of the entrances.*

7 DISCUSSION

7.1 Architectural expression

Slenderness is a key feature of designing both a solid shell and a gridshell. The thickness must be relative small compared to the span. Other gridshell solutions are more slender than the segment lath, and are visually even lighter structures. This due to the rhythmic space between the laths. On the other hand, the segment lath becomes almost solid from distance, the four layers merges into continues wowed laths. The result is a more harmonized and readable structure.

Figure 21: *Side view. The height of the entrances are approximately 1900 mm*

7.2 Material Consumption

The large overlap makes the segment lath consume more timber in the final structure. Hence the dead load is higher compared to a similar shape using another solution. That said, it is likely that the more compact solution also gains more strength, but no comparable studies have as yet been conducted. Furthermore, there is a difference between gross and net material consumption. The segment lath produces less waste compared to other solutions that demand continuous laths without any defects.

7.3 Scaling up?

The Trondheim Gridshell turned out to be a successful prototype. The main goal was to test the segment lath solution, and it performed as expected. There are also interesting issues yet to be examined to make the segment lath usable for architectural implementation. Cladding, connection to the ground and not least integrated bracing are also questions still to be answered. Furthermore, the segment lath itself has also a potential for a justified new version, but keeping the key-features. Current ideas are to add more layers, varying grid size, or even varying cross-section width in one structure.

One can also imagine the concept applied in a much larger scale. As explained in the chapter about schematic concept, the theoretical segment lath concept is scale-less. It is the materialization of the wireframe grid that determines scale, strength and use. If the grid where 1x1 meter and the thin laths were replaced by larger glulam beams, totally different implementations would be feasible.

Figure 22: Close-up *of the module*

8 CONCLUSION

This paper has investigated the potential of developing a simpler and more universal modular kinematic gridshell. The functionalities were tested in a full scale pavilion. The solution, the segment lath, revealed many advantages, including some that were not predicted. It also introduced some new interesting questions to be answered in the future. Following properties have been registered:

- The 400mm bypass connections function as shear-blocks when tightened.
- Each segment lath is connected to only one joint and the slotted hole can thus be moved to the bypass connection.
- The dead-load is larger. However it is unknown to which extent this is compensated by increased strength.
- The system is universal, meaning that it can replicate all types of quadratic grid shapes.
- The modulus is stackable by turning two of the laths 90°, making it suitable for transportation.
- Short laths make it easy to achieve high quality material and to replace broken parts during erection.
- Manufacturing/assembling is very simple and require almost no skills. The erection process is still demanding.

To summarize, through a series of simplifications, the segment lath solution has contributed to lower the threshold regarding construction of gridshells. The authors sees a great potential implementing the segment lath in large scale architectural projects.

Figure 23: *Gridshell seen from one of the foundation sides*

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