

Design, fabrication and assembly of a geodesic gridshell in a student workshop

Emil ADIELS^{*}, Nicolo BENCINI^b, Cecilie BRANDT-OLSEN^a, Al FISHER^b, Isak NÄSLUND^b,
Robert K OTANI^c, Emil POULSEN^c, Puria SAFARI^b, Chris J K WILLIAMS^d

^{*}Department of Architecture and Civil Engineering, Chalmers University of Technology
Gothenburg, Sweden

emil.adiels@chalmers.se

^a BIG Engineering

^b Buro Happold Engineering

^c CORE studio Thornton Tomasetti

^d Department of Architecture and Civil Engineering, Chalmers University of Technology

Abstract

This paper describes the design, fabrication and assembly of an 11x11 m gridshell built of plywood laths during a two and a half day workshop in a new undergraduate course about parametric design and digital fabrication. The question was how to use full-scale prototyping to summarize and integrate the learning outcomes in this course. A challenge was how to execute all production during two consecutive days utilizing all 35 students. Exploiting a geodesic grid design, that is curves whose curvature vector is parallel with the surface normal, the gridshell was made of straight predrilled laths that were bent and locked into shape using a sequential erection method. The design was incorporated in a full parametric model including automated design checks and the generation of all necessary production drawings. The workshop and the preparatory work described in this paper was a collaboration between Chalmers, BIG Engineering, Buro Happold and Thornton Tomasetti's CORE studio.

Keywords: Timber gridshell, geodesics, differential geometry, parametric design, digital fabrication, architecture and engineering, education and architecture, architecture workshop.

1. Introduction

A new course named *Digital tools -Parametric design (3 ECTS)* was planned and performed in 2017 by authors Adiels and Näslund for 35 undergraduates at the double degree program Architecture and Engineering (MARCH and MSc in Engineering) at Chalmers (Adiels, [1]). The main goal of the course was to give the students tools and knowledge necessary to sufficiently implement parametric design and digital fabrication techniques in their future projects, but also inspire them to practice their unique competence from both architecture and engineering. As an ending segment, a workshop of two and a half days was planned to showcase the full potential of parametric and geometric modelling in production. The scope was to build an indoor pavilion of a scale in which a group of people could stand and move freely. Equally important was to embrace architectural and engineering creativity using mathematics as a tool for efficient fabrication strategies. Industry specialists in the field of parametric design were invited to create a dialogue about present and future applications of digital tools in both academia and practice. The design, planning and execution of the workshop was a result of these conversations between Chalmers, BIG Engineering, Buro Happold Engineering and Thornton Tomasetti's CORE studio. The workshop started with half a day of explaining the theoretical background, the design process, and the parametric implementation, followed by two days for production and erection. Pictures from the finished project, a symmetric geodesic gridshell built from straight laths of plywood, can be seen in Figure 1.



Figure 1, the result of the workshop was a geodesic gridshell built from predrilled planar straight laths.

2. Background

The students had prior to this course been trained in both architectural, mathematical and engineering theory and methods through courses, workshops and architectural projects. This course is meant to integrate these tools in a digitally driven design process linked to digital fabrication techniques. The first part of this course had therefore focused on lectures and tutorials in the basics of parametric design and digital fabrication. These aspects were examined through assignments and smaller projects (Adiels, [1]). Since the earlier work covered and examined all course requirements it was possible to test if the learning outcomes could be summarized through a full-scale production in a workshop format.

This workshop builds on a workshop culture at Chalmers where engineering and artistic experiments are exhibited through digital tools and mathematical modelling. For example, Figure 2a shows a workshop where a brick vault is built on a falsework of plastic tubes that were actively bent into shape (Adiels, [2]).



Figure 2, a) A vaulting workshop using falsework from straight plastic tubes (Adiels, [2]), b) UWE Research pavilion (Harding et al [9]) c) The geodesic dome by Buckminster Fuller (Fuller, [3]).

Previous papers by authors have covered applications of geodesics in the design of textile (Williams [4]) and brick structures (Adiels et al [5]). Geodesics are curves on a surface that have zero geodesic curvature. Since they follow the shortest path on the surface they become straight when unrolled onto a plane (Struik [6]). Using the same notation as in Green and Zerna [7], a geodesic can be described as a unit speed curve with parameter t , lying on the surface described by position vector $\mathbf{r}$ with surface parameters θ^1, θ^2 (u and v in Struik).

$$\mathbf{r} = x(\theta^1, \theta^2)\mathbf{i} + y(\theta^1, \theta^2)\mathbf{j} + z(\theta^1, \theta^2)\mathbf{k} \quad (1)$$

The second derivative of $\mathbf{r}$ with respect to t , $\frac{d^2\mathbf{r}}{dt^2}$, is zero in the plane of the surface, giving the geodesic equation for the curves¹:

¹ Equation 2 does not only describe the geodesics in Figure 1 but also the paths of planets moving in space time.

$$\frac{d^2\theta^\lambda}{dt} + \frac{d\theta^\alpha}{dt} \frac{d\theta^\beta}{dt} \Gamma_{\alpha\beta}^\lambda = 0 \quad (2)$$

Geodesics have been applied in architectural projects such as the geodesic dome by Buckminster Fuller in Figure 2c, Ongreening Pavilion (Harding et al [8]), UWE Research Pavilion (Harding et al [9]) in Figure 2b, and the Almond Pavilion (Soriano, [10]). The geodesics of the dome are rather the result of the discretization of a sphere using the projection based on an icosahedron (Fuller, [3]). The other projects have used a geodesic design in combination with a material that allows for constructing its continuous laths from straight planar strips. The clear mathematical concept in combination with a low-tech and economic production strategy for gridshells was of much influence for the design concept in this project.

3. Limitations and preparations

For this project there were four restrictions that governed the design: (1) The design should use mathematics as driver for geometry and production in a way that is comprehensible for the students based on their previous knowledge and training. (2) Production of elements and erection must be done in two days. (3) The structure cannot exceed a height for which scaffolding is needed due to safety regulations. (4) The material cost should not exceed 1000 euro.

The workshop was to take place in our testing facility. The concrete floor which could not be penetrated, but its 1x1 m grid of apertures with 24 mm radius could be used for anchorage, see figure 3a. The production process was restricted mainly to manually operated machines and hand-power to produce and erect all elements. Therefore, the design was chosen to utilize flat straight laths of plywood made possible through a geodesic gridshell design. The design was to be incorporated in a full parametric model that includes everything from the form to the generation of all production drawings necessary to build the pavilion. These preparations were done in advance by the organizers of the workshop. The preparations for the workshop was divided in the following steps: (1) Materialize geodesics into structural elements. (2) Gridshell design (3) Link the design to automated generation of production drawings. (4) Structural analysis. The content covered in this chapter was packaged into lectures including theoretical background and a workplan used as an introduction to the workshop.

3.1 Material investigations

The mathematical concept of geodesics needed to be materialized into laths with a real material and cross section. The laths must be sufficiently stiffer in one direction to avoid curvature in plane of the surface and flexible enough in the weak direction to bend and twist using hand-power, but strong enough not break during erection. Figure 3b-d shows the physical experiments performed to investigate these parameters using 6 mm plywood of 50, 70 and 100 mm width, with and without connections. Laths were connected by overlapping adjacent elements and connect with two M6 bolts with steel washers on each side, similar to the Ongreening pavilion (Harding et al [8]). The cross section was chosen to be 50 mm wide and 6 mm thick birch plywood with 5 layers. This was the most economic and slender option with sufficient bending capacity. These experiments were important to get a feeling and understanding of the capacity and geometrical constraints needed for the gridshell design in 3.2.

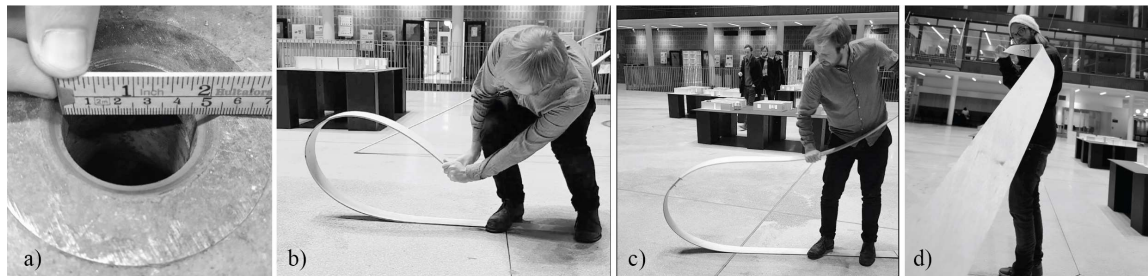


Figure 3a measurement of the aperture in the floor, b-d experiments investigating the capacity and user ability for different plywood laths.

3.2 Gridshell design

The form and pattern needed to integrate structural performance with a strict geometrical behaviour of geodesics in a materialized spatial experience. To create a geodesic, one must satisfy two boundary conditions either by fixing start and end points or starting point and direction. To control geodesic patterns one must either use quite intelligent rules and, or, interactively adjust the patterns depending on geometrical requirements (Pottmann et al. [11]). For this pavilion its geodesics could cross each other and therefore be modelled independently for visual inspection of the geometrical requirements, such as distance between connections and curvature of laths. Forms were examined using three approaches, see Figure 4, a) free-form b) analytical (mathematical functions) and c) behaviour driven design.

A symmetrical shape and grid had many advantages from a production perspective. It meant fewer unique building elements and simultaneous erection of similar sections. The gravity driven funicular shape, in combination with laths mostly forming arches, was thought to avoid large deflections and be stable during a sequential erection procedure. The final grid consisted of 8 different laths that were repeated 8 times through rotation and mirroring, see figure 5, making 64 laths in total. Each bottom curve was made using four points interpolated such that they aligned with the 1x1 m grid in the floor. This meant four possible attachments for the base plate following the bottom curve.

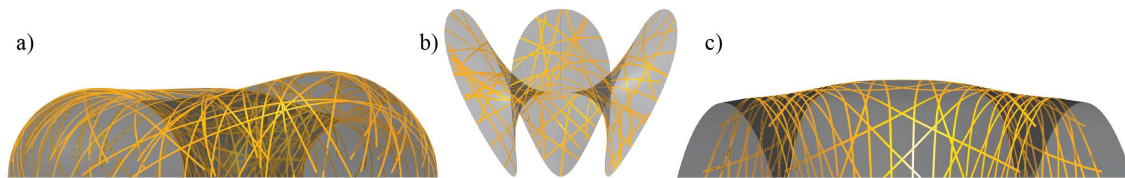


Figure 4, Different surface designs that were evaluated, the design to the right proved most efficient in terms of lath repeatability, lath adoption and structural efficiency.

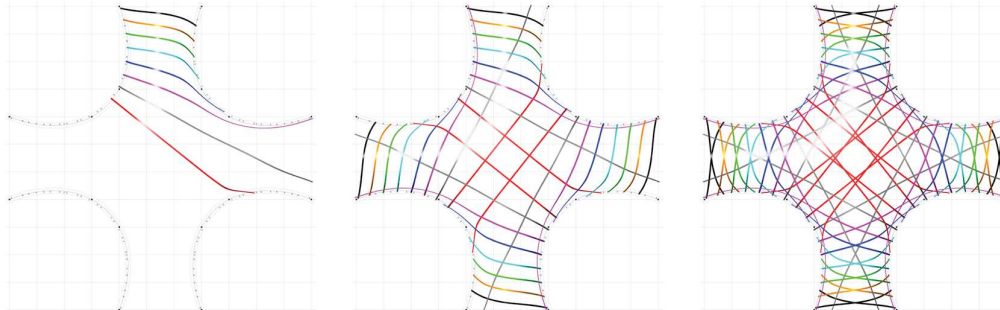


Figure 5, The lath layout strategy seen in plan with 8 unique laths repeated 8 times to form the complete layout. The orthogonal grid follows the 1x1 m grid of the aperture in the floor.

3.3 Parametric modelling and automation of production drawings

The parametric model was written in Grasshopper3d, a plugin to Rhinoceros3d, the development platform familiar to the students. It allowed for changes to be incorporated, such as tweaks to the surface and the lath layout, without any additional work needed for the visualization and the generation of production drawings. It also served as an example for the students on how to structure code and solve problems related to 1:1 prototyping. The code was divided into four sections: form finding, geodesic patterns, production drawings and visualization. This section will focus on the production drawings for the laths and base plates.

To generate geodesics on a surface, specific custom code was developed using the method described in Adiels et al.[5]². The geodesics on the gridshell became centerlines for developable surfaces with the same width as the laths. Since geodesics are straight lines on the surface, measured lengths along them maps directly to a straight line in a plane. If the geodesics are known, generating the production drawings

² Currently there was no functionality in Grasshopper3d to generate geodesics using starting point and direction.

becomes mainly a 1-dimensional exercise of measuring lengths. There were four steps in making production drawings for the laths: (1) Unroll the laths from the gridshell to a plane (2) Make holes for connecting laths crossing each other (3) Adjust the ends (4) Segment each lath into lengths fitting on a plywood sheet. To check that this was correct, the straight planar segments were used to rebuild the entire 3d model. This stage was essential to verify that all pieces fitted together correctly. These actions have been summarized in Figure 6a. All drawings necessary for all laths generated by the code can be seen in Figure 6b. For the baseplates, made of two layers of plywood anchoring the laths to the ground, only one drawing was needed. Due to symmetry and a minor adjustment of the seams the bottom plate could be flipped over without any continuous joints between the two layers. All code for this project is uploaded to a Github repository (Adiels et al. [12]).

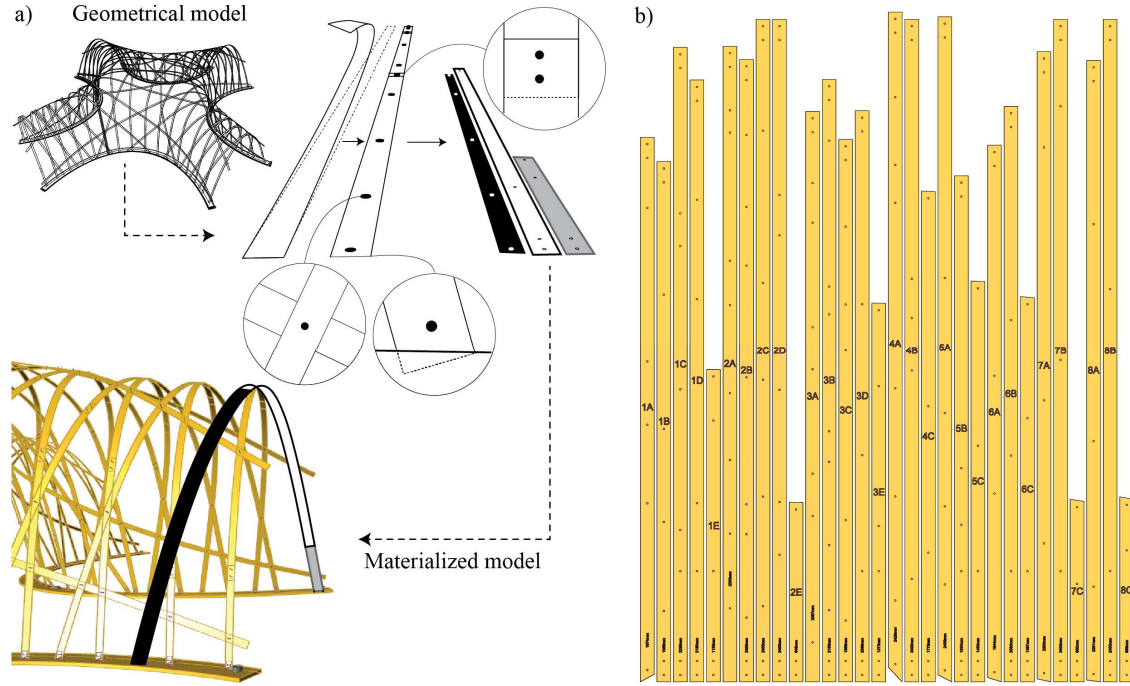


Figure 6a) Showing the process making the drawings for the laths. This includes unrolling, marking connections, adjusting edges and rebuilding the model using these drawings. 6b) shows all 30 elements needed to make all laths

3.4 Structural Analysis

Since the plywood strips used in the structure initially were straight, the elements had to be bent into position by utilizing the material's elasticity. To avoid material failure during erection and in final position, a basic bending stress check was performed. From the parametric model the curvature along each lath was evaluated at an equal distance from each other with sufficient frequency. The moment and equivalent maximum bending stresses were calculated using equation 3 for the desired cross section with material data from the supplier.

$$\sigma = M/I \times z, \text{ where } M = \kappa \times EI \quad (3)$$

The derived stressed stresses were checked against the materials bending capacity with the criterion $\sigma < f_{md}$. The analysis showed a slight over utilization near the openings. However, in the material tests in section 3.1 significantly higher curvature was observed, why the desired curvature was regarded feasible. Note that the check above only applies for the prestress induced by formation process.

To verify the structure's capacity to withstand the self-weight, a secondary analysis was conducted using a structural analysis plugin for Grasshopper 3d named Emu (Poulsen [13]). By using its' built-in time-stepping based non-linear solver, it could be verified that the structure was stiff enough to avoid global buckling failure from dead load.

4. Workshop – Building a geodesic gridshell

Before the building the pavilion, day zero, two lectures were presented describing the design process and the mathematical background behind the design. The entire parametric model was presented and handed out to give the students an idea of the added complexity compared to their earlier projects and assignments. The building of the pavilion was divided into one day for fabrication and one day for erection. Workstations were prepared in advance for the first day and divided in two sections, one for laths and the one for base plates and anchorage to the ground. Before fabrication started, all students assigned themselves to different predefined tasks for the morning and the afternoon. This was used to organize the fabrication and assembly of all elements such that the students were utilized as much as possible. Day 1 and 2 of the workshop was filmed (Adiels [14]).

4.1 Day 1 – Fabrication and assembly of all building elements.

All building elements were made using equipment in an adjacent wood workshop and power tools provided by our sponsor Cramo. The power tools consisted of 10 power drills with 6 mm bits, 2 chop saws and 2 jigsaws. The laths were made from 6mm birch plywood boards while the baseplates were made from two layers of 12 mm rough plywood. For attaching the laths to the baseplate, 112 steel angle brackets were used. In total, 728 M6 bolts with nuts and 1456 steel washers were used for connections.



Figure 7a) taping paper drawings onto wooden strips b) predrilling marked wooden strips c) the base plates were cut out using a CNC machine d) the base plates were made of two layers 12 mm plywood laminated using glue.

For the laths, 10 boards that were cut into 50 mm wide strips in the wood workshop. Meanwhile, other students printed 1:1 paper drawings for all 30 elements forming the 8 different types of laths when assembled. These drawings were cut and taped onto the wooden strips which were drilled and cut accordingly, see Figures 7a - b. These wooden templates were used to mark up the rest of the strips which were then processed in a similar fashion. After completing all 240 (8x30) strips, these were connected using M6 bolts and nuts with a washer on each side, forming 64 (8x8) laths in total.

For the baseplates, 8 boards were cut using a CNC machine in the wood workshop running a single drawing, see Figure 7c, which speeded up the cutting and reduced possibility for errors. The elements were laminated using wood glue and screws forming 4 identical curved plates, see figure 7d. The CNC machine also marked the placing of the steel angle brackets and cut holes that aligned with the apertures in the floor. Wooden poles, 40 cm in length, were made to fit the holes such that the base plates stayed in place due to friction between the poles and the concrete. The angle brackets were all at right angle when delivered and needed to fit the angle of the model. The angles ranged between 90 and 70 degrees and were therefore divided into 5 groups of 5-degree difference. Wooden blocks were cut at 85, 80, 75, 70 degrees and the angle brackets were hammered onto these to achieve sufficient angle. These were then attached to the baseplates using wooden screws.

4.2 Day 2 – Erection and assembly of gridshell.

All elements had been made and assembled to full length on the first day and second day was all about erecting and connecting all the predrilled laths into a gridshell. The assembly was done using a sequential erection procedure, illustrated in Figure 8, connecting the laths with bolts, nuts and washers using wrenches. Four teams would start, one in each opening, and work inwards. Before all laths could be established in this manner the laths in the centre were erected to support the remaining. The tolerance between the radius in the drilled holes and the bolts was very low, why the bolts often had to be screwed through the holes, rather than just being pushed through. The overall process went smoothly with good

alignment of the holes in the different laths. There were some exceptions to this, especially in the centre part of the grid where some force had to be applied to be able to connect the elements. One lath broke during the erection, due to a knot in the middle layer of the plywood, but a new lath could be cut and drilled from spares, which meant that the process could be resumed without much delay. Figure 9 shows various pictures from the erection and the finished pavilion.

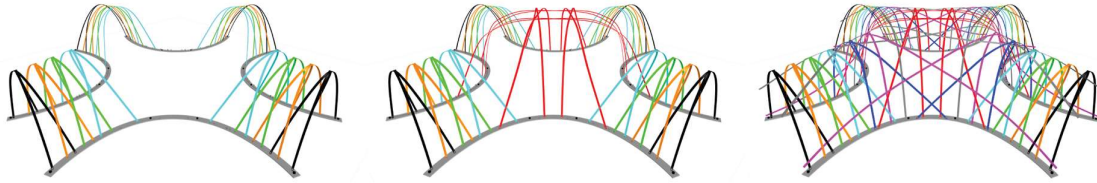


Figure 8, The procedure of erection, starting from the outside going inwards in four teams. The laths in the centre were needed to support the remaining laths.

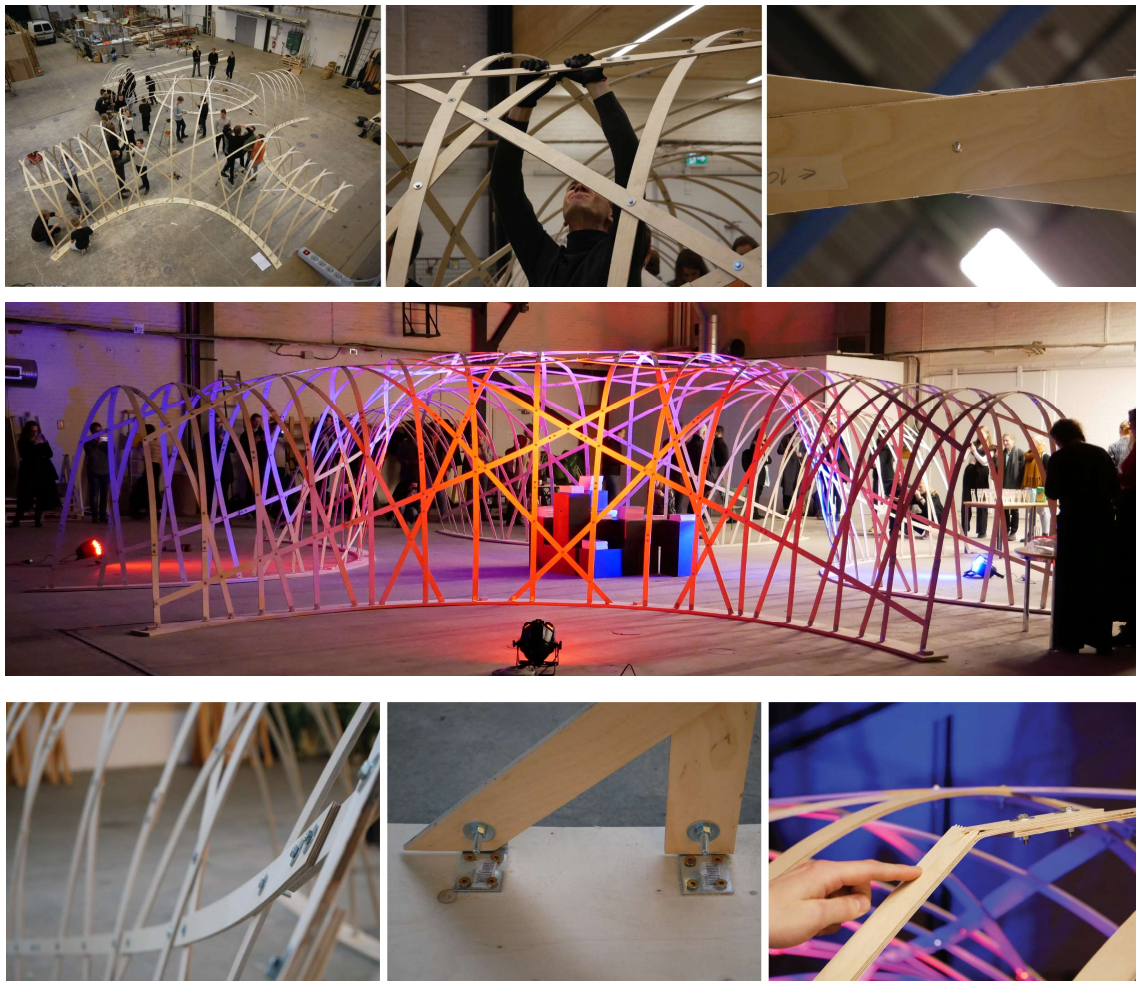


Figure 9, Various pictures from the erection along with the finished pavilion with some details.

5. Discussion

The main goal was to use full scale prototyping to summarize and integrate the learning outcomes in a course on digital tools and parametric design. Overall, we perceived the workshop as a success. In a course evaluation done after the workshop where 60 % of the students participated, the course was rated 4.8 out of 5, top 10 placement at Chalmers. This included the entire course where the workshop was roughly a third. Our biggest concern with the workshop, besides if everything would fit together, was if

the students would find it stimulating to build something that they had not designed themselves. We quickly realized that the students took ownership of the pavilion by taking control of the different workstations and fabrication processes. One area that could be improved was the drilling or marking on the laths. When assembled to full length on the floor some became curved. The solution was to expand the holes slightly and straighten them out. This could have been solved by having a larger tolerance between the holes and the bolts. The result however, came out almost perfect which means that the drawings and the work was well executed overall.

Two laths did break, one during erection and one when built. The first had a knot in the middle layer and the second broke near a connection in the finger joints of the plywood. However, there was never any danger. The material test did not consider possible defects in the plywood, and due to the small width, the laths were extra sensitive. These unexpected events effectively showed the students why design codes are necessary. However, a less stiff connection in combination with a curvature driven segmentation could have avoided the second failure. A simple adjustment could have been to use rubber or spring washers. Other improvements could have been to combine form finding with the generation of geodesics. This could have integrated the structural and the geometrical behavior in a more natural way.

There were two main reasons for the successful workshop - good preparations and the placement in time in relation to the student's other courses. The workshop was scheduled after their other examination period, meaning that the students could fully focus on the workshop resulting in a joyful atmosphere. We believe the workshop will inspire students to learn more about geometry and applications in digital tools. The material cost ended a bit over 1000 euros but compared to the learning outcome and the positive reactions it was a very low investment.

References

- [1] E. Adiels, "Digital tools – Parametric design course 2017." [Online]. Available: <http://emiladiels.com/digital-tools-parametric-design-course-2017/>. [Accessed: 15-Mar-2018].
- [2] E. Adiels, "Brick Workshop in Mariestad – Emil Adiels." [Online]. Available: <http://emiladiels.com/brick-workshop-in-mariestad/>. [Accessed: 11-Apr-2018].
- [3] R. B. Fuller, "Building Construction [U.S. Patent 2,682,235]," 1954.
- [4] C. J. K. Williams, "Defining and designing curved flexible tensile surface structures," in *The mathematics of surfaces*, G. J.A, Ed. Oxford: Clarendon Press, 1986.
- [5] E. Adiels, M. Ander, and C. J. K. Williams, "Brick patterns on shells using geodesic coordinates," in *IASS Annual Symposium 2017*
- [6] D. J. Struik, *Lectures on classical differential geometry*, 2nd ed. Dover, 1988.
- [7] A. . Green and W. Zerna, *Theoretical elasticity*, 2nd ed. Oxford University Press, 1968.
- [8] J. Harding, W. Pearson, H. Lewis, and S. Melville, "The Ongreening Pavilion," *Adv. Archit. Geom. 2014*, pp. 295–308, 2014.
- [9] J. E. Harding, S. Hills, C. Brandt-Olsen, and S. Melville, "The UWE Research Pavilion 2016," in *Proceedings of the IASS Annual Symposium 2017*
- [10] E. Soriano, "Low-Tech Geodesic Gridshell: Almond Pavilion" *archi DOCT* no 4., February, 2017.
- [11] H. Pottmann, Q. Huang, B. Deng, A. Schiftner, M. Kilian, L. Guibas, J. Wallner "Geodesic patterns," *ACM Trans. Graph.*, vol. 29, no. 4, p. 1, 2010.
- [12] E. Adiels, N. Bencini, C. Brandt-Olsen, I. Naslund, E. Poulsen, and P. Safari, "Github repository," 2018. [Online]. Available: github.com/archengtech/chalmersworkshop-dec2017.
- [13] E. Poulsen, "Structural design and analysis of elastically bent gridshells - The development of a numerical simulation tool," Chalmers University of Technology, 2015.
- [14] E. Adiels, "Geodesic gridshell workshop 2017." [Online]. Available: <http://emiladiels.com/geodesic-gridshell-workshop-2017/> [Accessed: 15-Apr-2018]