*Proceedings of the IASS 2024 Symposium*
*Redefining the Art of Structural Design*
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

# Simple top-down parametric method for designing timber gridshells using geodesic networks controlled along the boundary of translation surfaces

Rodrigo SHIORDIA LÓPEZ*, Juan Gerardo OLIVA SALINAS[a]

*Universidad Anáhuac México
Av. Universidad Anáhuac 46 Lomas Anáhuac. Huixquilucan. Estado de México 52786 México.
rodrigo.shiordia@anahuac.mx

[a] LEL Facultad de Arquitectura, Universidad Nacional Autónoma de México

## Abstract
Design of timber gridshells using physics simulation tools is normally done in a bottom-up approach where a flat network of laths with a constant nodal length is bent into a desired shape. Another approach is to apply the compass method from two geodesic curves onto a target surface. While these approaches are valid for conforming to many different target surfaces, they are hard to control along boundary conditions where the geodesic curve ends are not evenly spaced, and control of supports might be complicated. This paper presents an alternative method for deriving timber gridshell geometries from geodesic curve networks on translation surfaces based on boundary support spacing. Using parametric modeling, a geodesic curve network from a parabolic translation surface is obtained. Further trimming operations of the base surface can allow for design intent. The resulting curve network does not have a constant nodal length, but it can be flattened using Kangaroo. The design tool can calculate different geodesic networks of varying orientations. The parametric workflow allows optimization of the curve network orientation while maintaining uniform support spacing using evolutionary solvers. With a selected curve network, the straightening of laths into a flat configuration is simulated. Finally, a physical model is built to validate the results and determine viability. This approach is based on the intrinsic geometric simplicity of translation surfaces. With insights from Eike Schling's analysis of Zhuchov's Vyksa gridshell, the Darboux frame construction on the model is implemented to better approximate lath geometry. Finally, an accurate model is constructed using the straightened lath drawing. This model proved that the flat configuration can be deployed into shape while presenting other problems like complicated translations during bending. This approach can be a viable solution where even spacing between supports along the boundary of a timber gridshell is required.

**Keywords**: timber gridshells, parametric design, geodesic curve networks, elastic timber gridshell modeling.

## 1. Introduction
Elastic timber gridshells have been an important area of research in recent years. The availability of digital tools to model their behavior, along with the benefits of using timber as a renewable construction material area some of the reasons that timber gridshells are a viable solution for low weight efficient structures.

Another advantage of using elastic timber gridshells is the relative simplicity of node geometry compared to other structural systems. Node geometry in these structures is normally composed of a bolt that fastens several layers of planks arranged in a net-like mesh.

The fundamental aspect of the design of timber elastic gridshells is the correct computation and implementation of an accurate network of flat laths that is bent to achieve a target surface. There have been different approaches to this challenge. The main approaches are physical modeling, physical simulation, and analytic or numerical models.

In the case of physical modeling, Elastic timber gridshells are normally designed using a bottom-up method where a model of flat grid of connected laths is deformed, into shape. The Mannheim Multihalle by Frei Otto, and the Downland Gridshell was designed using a metal wire mesh model [1] [2]. These models were constructed with constant nodal lengths, and the grid was laid out flat and deformed into shape. When doing a scale model, the nodal length is approximated, and a higher nodal length is used to have a manageable model. In the Mannheim model, the scale model represented every third lath in the actual structure.

The computational modeling of geodesic curve networks relies on the correct computation of the geodesic curve. A geodesic curve that lies on a surface is a curve that with curvature around the normal vector of the surface at all points on the curve approaching zero. Pirazzi and Weinand's work describes a method for this computation that has as an input a start and ending point on the surface [3]. Once these curves can be computed and modeled, the challenge remains of deriving a suitable network.

Another approach is to digitally simulate the bending of a lath network. Soriano presented a method for simulating the bending of a net of lines to approximate the shape of a bent network which is close to the geodesic network on the target surface [4]. This approach starts from a flat net of curves that are simulated as rigid rods. The supports or boundary conditions are then moved towards a target anchor point, and the network's curvature is found through the simulation of the rods' stiffness.

Both Weinand [3]and Soriano [4] draw their curve networks onto a surface with four sides, and the boundary conditions normally have equidistant node spacing as well as nodes with valence 2, meaning that there are two curves that start or end in a given boundary node. This level of control along the boundary conditions is highly desirable for ease of construction and structural performance. Equidistant supports reduce complexity on construction. The disadvantage of this method is that one must accurately find the support points along all four boundary curves. This is problematic when using trimmed surfaces as every support along a boundary of a trimmed surface is hard to calculate. There is a deviation between the geodesic network along the untrimmed and trimmed surface.

Finally, a third approach is the so-called Chebyshev method. This is also called the compass method. It starts with a pair of geodesic curves that intersect at a point on a surface. A network from these two curves is calculated. A specified distance is computed from the starting point along both curves. Once these two points are found, a final point is found by computing a point on the surface that is equidistant from these two points. A starting quad is found by connecting the original point with the three found points. This process is repeated recursively in all directions, and the resulting curve network is called the Chebyshev network [5].

When using the Chebyshev method, there are an infinite number of Chebyshev nets that can be applied to the surface [6]. The angle between the starting curves is what allows to have many different networks. However, this method has the disadvantage of being unpredictable along boundary conditions. One cannot easily control support spacing or the number of elements on any given support along the boundary curve. Such is the case in the gridshell described and designed by Lara Bocanegra [5]. The advantage of this method is the regular spacing between nodes, as the nodal length is always the same.

All the above methods are focused on the computation of the flat network of curves from a curve network on the target surface, however, the control of the supports along the boundaries are not discussed in their work. Analysis of these methods found the need to study support simplicity for ease of construction as a starting point in the design phase.

This work is an implementation inspired by these methods into a simple workflow for using translation surfaces and their simplicity to generate viable curve networks. We automate the generation of a curve network based on boundary conditions (support spacing) that can help optimize the performance of elastic timber gridshells in the design phase. The workflow is presented in the design and modeling of a 13 by 23-meter timber elastic gridshell, and the construction of a 1:25 physical model.

## 2. Methodology

There were some important criteria in defining the method to be used for our approach. Firstly, the structural behavior of the gridshell should have a catenary or parabolic geometry to ensure optimal structural performance. Second, the grid shell would be supported on an arched beam to have supports at the corner. Third, supports along the beam were to be simplified as much as possible.

Our objective is to find ways of optimizing the structural performance of elastic timber gridshells based on translation surfaces while simplifying support conditions along the boundaries. To achieve this goal, we created a multi-step tool entirely within the Rhino/Grasshopper environment. We first created a parametric model of a translation surface. From the parametric model, a suitable geodesic curve network is computed using native Grasshopper components. The orientation of the curve network is a customizable parameter. Once we have a curve network, we analyze its structural performance using Karamba 2.0 Finite Element Analysis [7]. The results from this analysis are used as a fitness function for optimizing structural performance using simple Galapagos Evolutionary Solver native to Grasshopper. Curve network orientation and base surface geometry were the main customizable parameters that the solver could change.

Once a design solution is found, we tested some of the initial assumptions. The first test was the computational simulation of a flattening of the curve network using Kangaroo Physics. This test was performed to validate the constructability of the model from a flat network. Second, we built a 1:25 physical model to test the simplicity of assembly. Analysis of both the complexity of construction and the precision of the model will provide insights into the viability of our approach.

### 2.1 Base surface

Our base surface is a simple translation surface with a parabolic arch as a directrix and a smaller parabolic arch as a generatrix. The directrix and generatrix are orthogonal to each other. The parametric model allowed to change the ratio of rise to span. However, this ratio was constrained to less than 0.25. When the ratio of rise to span of a parabolic arch is less than 0.25, the deviation from a catenary arch is very small [8]. This approximation was done because drawing a parabolic arch from three points is significantly easier than drawing a catenary arch using Grasshopper native components. It is also computationally faster in our workflow. This base surface helped to codify initial design intent and test the overall form of the model.

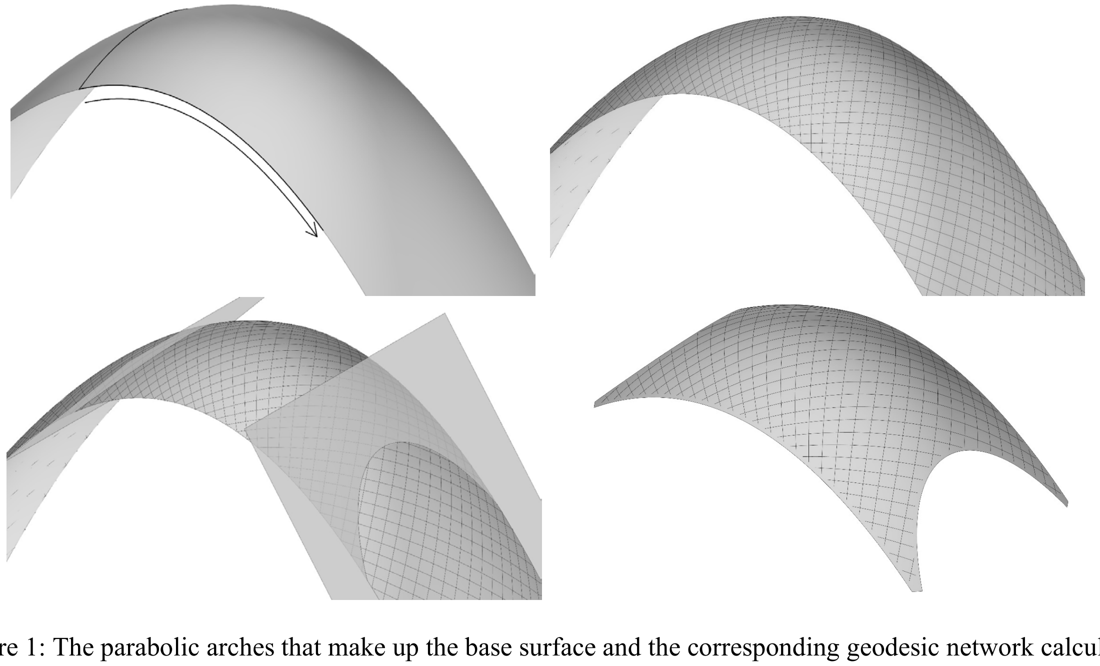

Figure 1: The parabolic arches that make up the base surface and the corresponding geodesic network calculated from the division of the directrices.

## 2.2 Geodesic Curve Network

Once we had the base surface parametrically modeled, we extended the directrix curve to have a larger base surface. The surface extension is necessary because the curve network will be drawn from opposite division points along the two boundary curves parallel to the directrix. Both boundary curves are divided using one of two modes, equidistant mode, or using parallel planes. Equidistant mode uses distance along the curve. Parallel planes mode uses parallel planes intersected with the curve to find the division points. This allows for a high degree of control of the support spacing along the boundary of the surface. The geodesic curve network is modelled by drawing the geodesic curve from a point along the boundary to a shifted point along the division points of the opposite boundary. This shift helps to control the average angle at the nodes. Smaller shifts will result in steeper angles in one direction, larger shifts result in more shallow angles in the same direction.

## 2.3 Model Optimization

Once the initial curve network is generated, the structural performance was evaluated as a straight beam model in Karamba 2.0. Straight sections between nodes were the chosen approximation. The prestress induced by bending was considered as a lower allowable stress for the overall model. We used generic Young’s modulus and other material properties for medium quality timber. Dead and live load cases were calculated using local building code combinations. The output from this stage was a maximum displacement value that could be used as a fitness function in simple evolutionary solver Galapagos. We also had a maximum stress both in compression and tension.

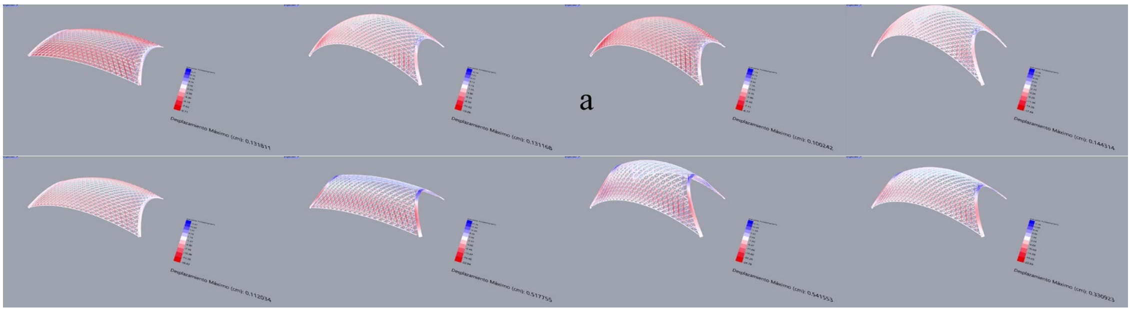


Figure 2: Different rise to span ratios of the evolutionary solver. Option marked (a) showed the optimum rise to span ratio. Maximum stress was +/- 8kg/cm². Maximum displacement was 0.1cm. Note that these options do not show change in curve network orientation, rather change in rise to span ratio.

The evolutionary solver then iterated through several options of curve networks, where parameters like the spacing between support points, and the angle of the gridshell, controlled by the shift on the opposite division points were the main parameters that could be changed. We also allowed the solver to iterate through some very constrained ranges for the rise and span of the generatrix arch. The orientation of the gridshell, the average angle of the laths at the node, rise to span ratio of the base surface arches, and the rotation of the trimming planes at the ends of the gridshell were the parameters that the evolutionary solver could modify. The evolutionary solver iterated through many different curve networks to find an optimal gridshell geometry on the same base surface.

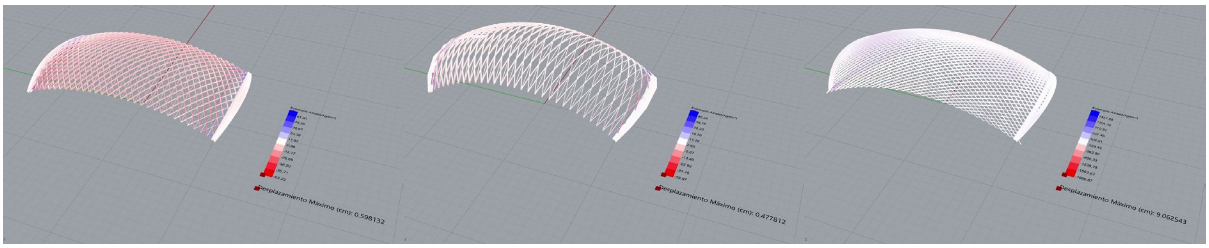

Figure 3: With similar rise to span ratios, several different curve network orientations. The shift of the curve network controls the curve network orientation. Note that the trimming of the base surface is different in this iteration.

## 3. Analysis of the resulting curve network

Once a geodesic curve network is found, we used Kangaroo Physics to simulate the flattening of the curve network. This analysis is made to determine if, as is the case in Soriano's G-Shells[4], we have a developable curve network. The resulting curve network was flattenable. The simulation only included bending and did not include torsion.

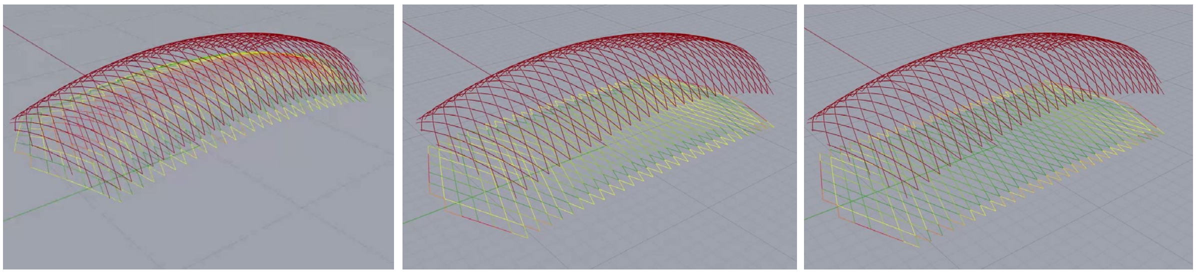

Figure 4: Different stages in the flattening process of one of the curve networks. Color in the flat state indicates deviation from the starting nodal length. This deviation was under 1mm.

The curve mesh was again approximated as straight sections between each node, and the angle on each continuous lathe was targeted to approach 180°. Also, the straight sections were constrained against compression or tension. The first simulations showed that this straightening force was not enough to flatten the network swiftly. Gravity was introduced and equilibrium was much more swiftly found. This gravity force, while it doesn't necessarily represent an actual physical process, does not change the geometry of the laths. The geometry that changed on the flat configuration was the angle between laths.

The simulated flattening of the network validated the approach as expected, but further testing with a 1:25 physical model was done to determine the inverse process: to have the flat network and bend it into shape.

## 4. Modeling Layered Elastic Timber Gridshells

Once a suitable curve network is found, there remains the challenge of modeling the gridshell layers. In these structures, layers are used because added layers increase rigidity of the structure, however, the elastic bending is harder for larger sections. Laths are normally bent along their weaker direction, and the layering technique, present since Mannheim Multihalle is the solution for bending the elements while adding a correct depth to the overall shell. To model the different layers of the gridshell, we used the normal direction of the surface at every node location and computed the Darboux frame from this information. The Darboux frame is constructed using a curve on a surface. At a point along the curve, the normal direction to the surface is one direction of the frame. The tangent direction to the curve is the second direction of the frame, and the cross product between these two vectors corresponds to the third direction of the frame [9]. Using this frame on the nodes of the curve network, it is easy to model the different layer geometry.

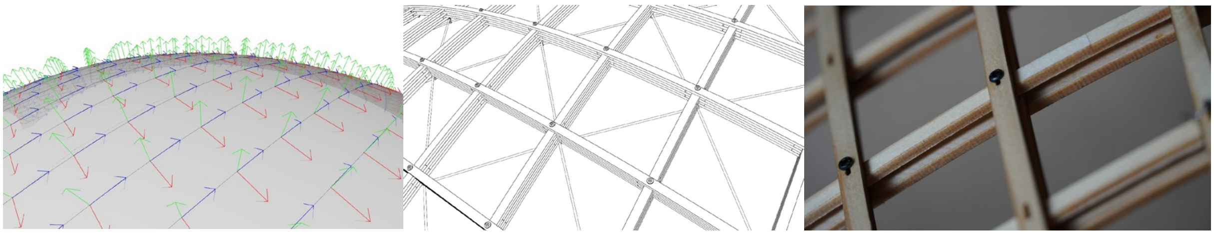

Figure 5: The Darboux frame construction is essential to accurately model all the layers of the gridshell. From the information in the model, the Darboux frame is essential in all the stages of the construction of the model.

### 4.1. Physical model

For the physical model, a suitable scale of 1:25 was chosen where the laths were modelled using ponderosa pine that was laser cut to have the required nodal distance and bolt slots. The first layer was mounted on the supports one lath at a time, while the second layer was first bolted on flat, and bent into position on top of the first layer.

Figure 6: The completed physical model shows the viability of the construction process. The curved laths were easily assembled thanks to laser cutting the laths. Note the regularity of the support points along the boundary of the longitudinal arch.

The second validation test that we performed was the ability to bend the network from the flat configuration in the physical model. The flat configuration, as well as the curved state, have different nodal lengths. For the construction of the model, we first constructed the first layer of the laths directly onto the support arches. The second layer of the laths was then fixed onto the model from the flat state. One observation from this process is the compaction of the flat state as compared to the curved state. This is necessary because of the different nodal lengths which do not allow for a flat configuration that spans the whole model. The flat state is compact, and the quadrilaterals are elongated on the transverse direction of the gridshell. However, on the curved state, the quads are elongated on the longitudinal direction, expanding the curve network on that direction. These translations are significantly large proportional to the length of the gridshell and correct manipulation of this process in a full-scale environment would be difficult.

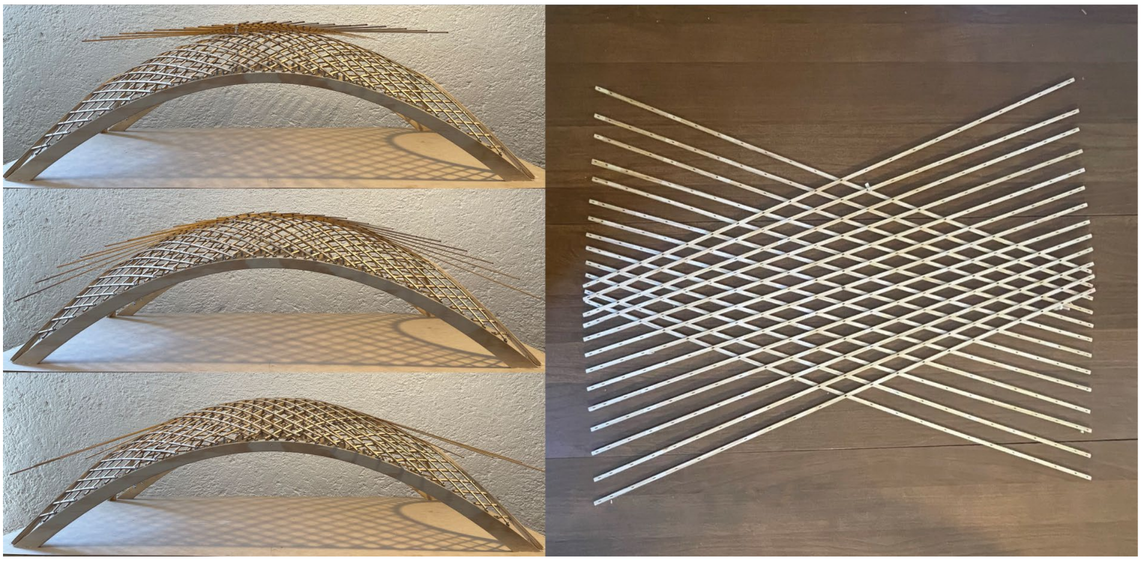

Figure 7: A single layer of the flat network was tested onto a first layer already in place in the model. This process was accurate, and the network was able to bend into shape at the desired nodes and supports, showing that the flat network is indeed deployable.

## 4.2. Support mount geometry

While the curve network was generated using the same points as the start and end points of the curves, meaning that each support point of the gridshell receives two curves, one for each layer, a further modification was done to make construction of the model easier. To have one single lath arriving at each support, the network was trimmed a given direction from the support. Since the curve endpoints were regularly spaced, the resulting individualized supports were also regularly spaced.

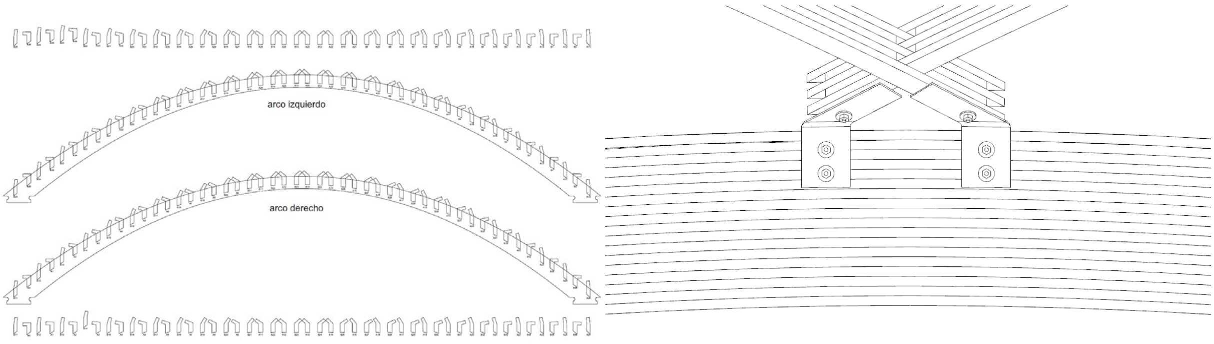


Figure 8: Drawings of the regularly spaced location of the support mounts in the physical model, and a representation of the support mounts in the digital model.

Each support was created using the new curve end points and their tangent vectors at those points, from there, also using the explained Darboux frame construction, a support mount geometry was parametrically developed from this frame and a vertical plane at the curve endpoint. This allowed for laser cutting support mounts from aluminum and each support only has a single fold line. This approach made the assembly of the model much easier. A double support mount was considered but discarded due to the difficulty of bi-directional support. Our review of different design methods regarding supports and boundary conditions did not find a lengthy discussion of support geometry generation, but this was one of our main considerations because of the simplicity of construction. Our support mount geometry proved easy to assemble in the physical model, and a similar geometry could prove viable in a full-scale construction setting with little changes to the methodology. While in the model we used thin aluminum sheet, in a full-scale implementation these would be steel sheet metal supports.

## 5. Conclusion

The method we used takes the shortcomings of the methods described in the first section into consideration for creating a curve network from a translation surface. The method we are using first calculates a geodesic curve network of an untrimmed translation surface using evenly spaced support endpoints at opposite boundary edges of the surface. This approach has regularity and ease of construction in untrimmed edges of the base surface.

Our method uses native grasshopper components in a parametric workflow to calculate all the model geometry and curve network. The resulting curve network is flattenable into a flat configuration and the physical model able to be built using the flat network as a starting point.

This frame is presented by Eike Schling in his analysis of Zuchov's bent networks [9]. Our final model is inspired by this important project, but our focus is on the structural optimization of both the rise to span ratio of the base surface, and the curve network orientation to deal with different load cases.

While the analyzed examples have solved many of the same problems that we encountered, boundary conditions are not the normal way of approaching the design of gridshells, but regularity in support spacing could be one of the most desirable features of a design intent. Our approach takes boundary condition requirements as a starting point and develops the ideas from important research in the field to present a viable workflow for simple gridshells.

Further work is necessary to apply this level of control to with other types of boundary conditions like more complex three-dimensional space curves. Also, different base surface geometries need to be explored. Our base surface used parabolic arches as directrix and generatrix curves to construct the model of the surface, but using catenary curves is yet to be explored.

The method we present does have the disadvantage of using large translations and rotations in order to bend the flat network into the curved state. This could prove difficult in a larger scale where large hoisting equipment might not be available. Other methods to deal with this constraint are the segmentation of the gridshell into pre-bent discrete parts. This approach might be studied further.

The methods described can be effective in computing suitable curve networks that can be used to model elastic timber gridshells, particularly when using translation surfaces and a high degree of control of support geometry is required.

## Acknowledgements

This research has been conducted under the Specialization program in lightweight structures of the National Autonomous University of Mexico. Special thanks to Marcos Javier Ontiveros.

## References

[1] I. Liddell, "Frei Otto and the Development of Gridshells," *Case Stud. Struct. Eng.*, vol. 4, Aug. 2015, doi: 10.1016/j.csse.2015.08.001.

[2] R. Harris, J. Romer, O. Kelly, and S. Johnson, "Design and construction of the Downland Gridshell," *Build. Res. Inf. - Build. RES Inf.*, vol. 31, pp. 427–454, Nov. 2003, doi: 10.1080/0961321032000088007.

[3] Y. Weinand and C. Pirazzi, "Geodesic Lines on Free-Form Surfaces - Optimized Grids for Timber Rib Shells," 2006. Accessed: Apr. 11, 2024. [Online]. Available: https://www.semanticscholar.org/paper/Geodesic-Lines-on-Free-Form-Surfaces-Optimized-for-Weinand-Pirazzi/c27aef9d3b42414a6077646abcbf6f8abf402312

[4] E. Soriano, R. Sastre, and D. Boixader, "G-shells: Flat collapsible geodesic mechanisms for gridshells," presented at the IASS Annual Symposium 2019 – Structural Membranes 2019, Oct. 2019.

[5] A. J. Lara-Bocanegra, "Elastic timber gridshells. From material to construction," 2022.

[6] D. Naicu, R. Harris, and C. Williams, "Timber gridshells: Design methods and their application to a temporary pavilion," presented at the WCTE 2014 - World Conference on Timber Engineering, Proceedings, Aug. 2014.

[7] C. Preisinger and M. Heimrath, "Karamba—A Toolkit for Parametric Structural Design," *Struct. Eng. Int.*, vol. 24, no. 2, pp. 217–221, May 2014, doi: 10.2749/101686614X13830790993483.

[8] E. Allen and W. Zalewski, "Chapter 3: Designing a Cylindrical Shell Roof," in *Form and Forces: Designing Efficient, Expressive Structures*, 1. Aufl., New York: Wiley, 2012, pp. 65–67.

[9] E. Schling and R. Barthel, "Šuchov's bent networks: The impact of network curvature on Šuchov's gridshell designs," *Struct. Oxf.*, vol. 29, pp. 1496–1506, 2021, doi: 10.1016/j.istruc.2020.12.021.

*Proceedings of the IASS 2024 Symposium*
*Redefining the Art of Structural Design*
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine De Wolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

# Copyright Declaration

Before publication of your paper in the Proceedings of the IASS Annual Symposium 2024, the Editors and the IASS Secretariat must receive a signed Copyright Declaration. The completed and signed declaration may be uploaded to the EasyChair submission platform or sent as an e-mail attachment to the symposium secretariat (papers@iass2024.org). A scan into a .pdf file of the signed declaration is acceptable in lieu of the signed original. In the case of a contribution by multiple authors, either the corresponding author or an author who has the authority to represent all the other authors should provide his or her address, phone and E-mail and sign the declaration.

Paper Title: **Simple top-down parametric method for designing timber gridshells using geodesic networks controlled along the boundary of translation surfaces**

Author(s): Rodrigo Shiordia López*, Juan Gerardo Oliva Salinas**

Affiliation(s): *Universidad Anáhuac México, ** LEL Facultad de Arquitectura, Universidad Nacional Autónoma de México

Address: Av. Universidad Anáhuac 46 Lomas Anáhuac. Huixquilucan. Estado de México 52786 México.

Phone: +52 55 4374 9977

E-mail: rodrigo.shiordia@anahuac.mx

---



Printed name: Rodrigo Shiordia López Signature: ____________

Location: Mexico City Date: July 1st 2024