

# Construction system for reversible self-formation of gridshells

Correspondence between physical and digital form

Efilena Baseta  
University of Applied Arts  
Vienna

Klaus Bollinger  
University of Applied Arts  
Vienna



## ABSTRACT

This paper presents a construction system which offers an efficient materialization method for double-curved gridshells. This results in an active-bending system of controlled deflections. This system embeds its construction manual into the geometry of its components. Thus it can be used in a self-formation process. The two presented gridshell structures are composed of geometry-induced, variable stiffness elements. The latter elements are able to form programmed shapes passively when gravitational loads are applied. Each element consists of two layers and a slip zone between them. The slip allows the element to be flexible when it is straight and increasingly stiff when its curvature increases. The amplitude of the slip defines the final deformation of the element. As a result, non-uniform deformations can be obtained with uniform cross sections and loads. When the latter elements are used in grid configurations, self-formation of initially planar surfaces emerges. The presented system eliminates the need for electromechanical equipment since it relies on material properties and hierarchical geometrical configurations. Wood, as a flexible and strong material, has been used for the construction of the prototypes. The fabrication of the timber laths has been done via CNC industrial milling processes. The comparison between the initial digital design and the resulting geometry of the physical prototypes is reviewed in this paper. The aim is to inform the design and fabrication process with performance data extracted from the prototypes. Finally, the scalability of the system shows its potential for large-scale applications, such as transformable structures.

- 1 Suspended self-formatted gridshell consisting of geometry-induced variable stiffness wooden laths.

1

## INTRODUCTION

Unlike shipbuilding, automotive, and aircraft industries, the building construction industry remains labor intensive. In an attempt to create novel, efficient construction processes, architects and engineers have sought inspiration in natural systems. Observing living organisms, scientists found that they are able to form hierarchically organized structures through genetically controlled self-organization (Knippers, Nickel, and Speck 2016). By reverse engineering, applying hierarchical principles in man-made structures, self-organized systems can emerge.

The programmed movement of self-actuating mechanisms that exist in nature (e.g. pine cones or wild wheat awn) relies on bi-layer structures. In the latter structures, one part responds to the stimuli, activating the movement, and the other part restrains the kinetic behavior. In addition, the differences in the geometrical characteristics of the parts (e.g., fiber orientation and swelling factor) define the deformation (Burgert and Fratzl 2009). Being inspired by the aforementioned system, the presented research focuses on the development of a double-layered linear element (beam), where the geometrical configurations between the two layers control its deflection. The results are scalable active-bending elements with controlled deflections. These elements embed their construction manual into the geometry of their components; thus, they can be used in self-formation processes.

According to Frazer (2015), design complexity can emerge through simple elements and rules. As a result, when the aforementioned elements are combined in a gridshell system, the self-formation of double-curved surfaces can be obtained (Figure 1). According to the systemic approach, the behavior of a system is controlled through the knowledge of the components and how these components interact (Alexander 1964). Therefore, the principle of operation of the discussed elements, as well as the performance of two gridshells, are described in this paper. The aim is to inform and evaluate the developed construction system with performance data extracted from the prototypes.

## BACKGROUND IN ACTIVE BENDING STRUCTURES

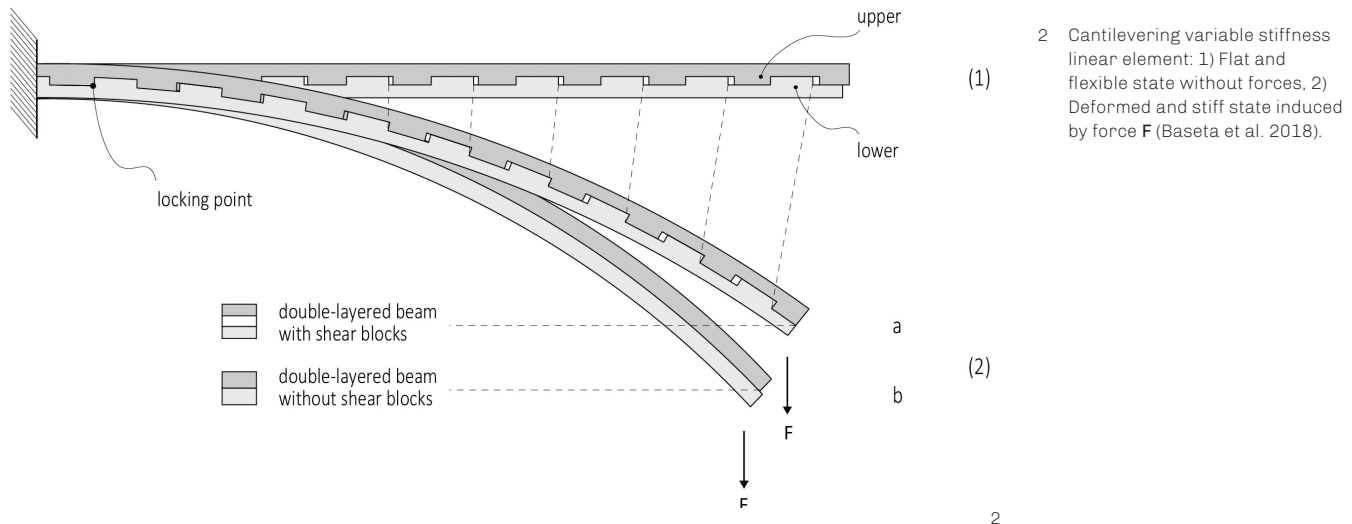
Active bending is an efficient form-giving process which exploits elastic deformation to shape initially straight linear elements or planar surfaces into curved configurations. It has been widely used in vernacular architecture since it is a simple construction method for deployable, lightweight structures such as yurts (Lienhard et al. 2013a). The last 50 years, active bending has been widely used for the construction of large-span gridshell structures. This is due to economic reasons and more specifically due to: a) volume

reduction for transportation, b) a single production process for elements with different radii of curvatures and c) structural performance and adaptability (Gengnagel et al. 2013).

Nevertheless, the disadvantage of the aforementioned form-giving process is the initial stress caused to the elements by bending. This has been apparent during the erection process of large span gridshells where many breakages occurred. For instance, during the erection of the Mannheim Multihall, extra shear blocks had to be added manually between the layers of the gridshell in order to increase its stiffness and stability (Liddell 2015). In order to reduce the stress for a specific material, either the cross-sectional height should decrease or the radius of curvature should increase. This is a conflict due to the fact that a smaller cross-sectional height reduces the stiffness of a structure and a bigger curvature radius limits the design possibilities of curved structures. An optimized active bending structure would allow small radii of curvature and obtain high stiffness. The aforementioned conflict results in scaling limitations of active bending structures, which also depends on the strength of the material used (Lienhard and Knippers 2013; Gengnagel et al. 2013). According to recent studies, the most efficient materials for active bending are wood, GFRP and NFRP (Kotelnikova-Weiler et al. 2013).

To overcome the scaling limitation, researchers developed hybrid structures. In these structures, elements such as textiles or cables are added to stiffen the bent elements. Thus, the cross-sectional height can be reduced as well as the radius of curvature. One precedent of this construction method is the MoD-shelter, which consists of membrane-restrained arches which span 5 m (Gengnagel et al. 2013). Another precedent is the M1 which consists of actively bent rods restrained by a membrane (Lienhard et al. 2013b). Other approaches to overcome the low stiffness of bending active structures have been conducted with the StretchPLAY prototype. For this prototype, laminated beams were created by bundling together three GFRP rods with a knitted sleeve. In order to remove the shear between the three rods, and thus increase the overall stiffness, the laminated beams were impregnated with epoxy resin once the structure was shaped in its curved shape (Ahlquist 2015).

A further advantage of bending active systems is their flexibility. This property allows the creation of compliant mechanisms. Thus, bending active systems can find applications in elastic, kinetic, and shape adaptable structures. However, precedents of the latter structures remain at component scale, supported and controlled by electro-mechanical equipment. Recent examples are the kinetic



louvers Flectofin and Flectofold as well as the adaptive photovoltaics of the Softhouse (Lienhard et al. 2013a; Körner et al. 2016; Lienhard and Knippers 2015). One example of self-supported transformable structures has been realized recently which relies on biaxial braided systems. Nevertheless, this structure remains at an experimental stage due to its limited freestanding capabilities (Sparrman et al. 2017).

Given the above, the presented research aims to offer alternative ways to achieve scalable active bending structures with a more efficient stiffness-radius relation. The developed system eliminates the need of additional elements (e.g., membranes, cables, shear blocks) and stiffening processes after assembly (e.g., impregnation of laminated beams). In addition, it intends to facilitate the realization of self-supported shape-adaptable structures by creating variable stiffness elements.

## GEOMETRY-INDUCED, VARIABLE STIFFNESS SYSTEM

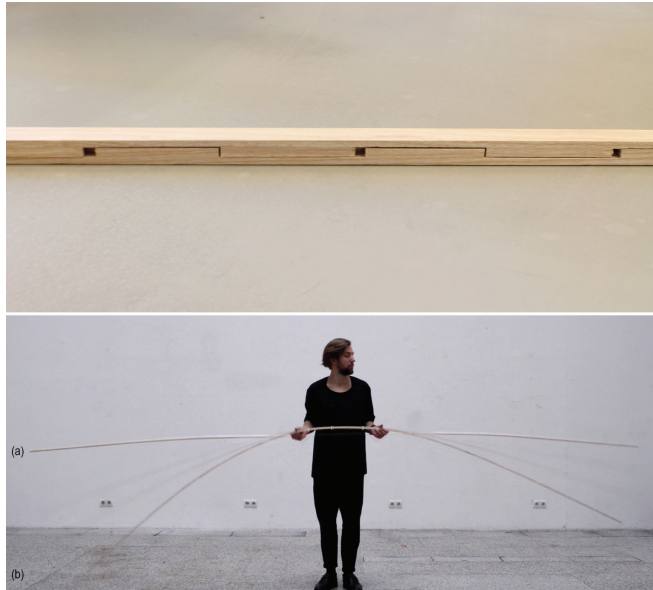
The principle of operation of the proposed system relies on multiple bending-active linear elements (laths) placed on top of each other. This multi-layered (minimum two) element, exploiting the small cross section of its parts, is susceptible to deformations. By embedding shear blocks between consecutive layers, the stiffness of the elements is increased, similarly to the construction strategy of Mannheim Multihall (Liddell 2015). In a double-layered element, the successive shear blocks are alternated between the top and bottom (Figure 2). By leaving gaps between successive shear blocks, relative slip between the upper and lower layer is allowed when loads are applied. By designing the lengths of the aforementioned gaps based on strain values, controlled deformation can be obtained (Baseta et al. 2018).

More specifically, to design a linear element of controlled deformation, a 'bent' curve that represents the desired shape should be provided. Additionally, the desired material and boundary conditions of the elements should be known. Subsequently, the aforementioned data are input in an algorithm. The algorithm analyzes the data set in terms of curvature and bending behavior and outputs the number of layers needed as well as their cross section. Knowing the cross sections and the height of the shear blocks, the strain values along the element with a specific locking point (the point where the layers are fixed) are calculated by another algorithm (Baseta et al. 2018).

The connecting geometry between the upper and the lower layer of each element is based on repetitive tabled scarf joint details (a 'tooth' like detail). As shown in Figure 3, when a cantilevering element is flat, the gaps appear at the right side of the shear blocks of the lower layer. However, when it reaches its maximum configuration, the gaps appear at the left side of the aforementioned shear blocks. This is owing to tensile forces exerted at the top surface of the bottom layer, and compressive ones exerted at the bottom surface of the top layer respectively. As soon as the initial gaps are closed, the slip is blocked and the predefined elastic deformation is reached. As a result, a stiffer configuration with enhanced cross section height is obtained (state 2 in Figure 2). When the load is removed, the structure returns to its initial unstrained state (state 1 in Figure 2). Thus, when the abovementioned uniform elements are used in gridshell configurations, they create initially flat surfaces which are able to shift from planar to a predefined double curvature by the presence of uniformly distributed loads.

Double-layered elements with tabled scarf joint details have been used for the gridshells presented in this paper. This specific geometry blocks upward deformations (Figure 3);





3 Top: Double-layered variable stiffness element with tabled scarf joint detail. Bottom: State (a) shows the element straight and stiff when its top layer faces upwards. When the element is rotated 180° around its longitudinal axis (top layer faces downwards) it becomes flexible and starts to deform until it reaches its predefined bent state (b) where it reaches again its maximum stiffness.

however, variations of the shear block geometry can lead to different behaviors and thus applications of the system. Finally, the variation in the number of layers and their cross section dimensions make the system scalable.

Physical experiment has been chosen as a method to evaluate the performance of the aforementioned geometry-induced, variable stiffness elements for the self-formation of gridshells. Thus, two experimental structures with different boundary conditions have been built. The design and digital fabrication process of the latter prototypes are reviewed in the following section.

## PHYSICAL PROTOTYPES

### Suspended Gridshell

The first prototype refers to a suspended double curved gridshell (6 x 3 m footprint). The design has been realized by digital form-finding processes. More specifically, gravitational loads have been applied to an initially flat mesh. The equilibrium state of the specific mesh and loads was frozen and discretized into a distorted (30°) rectangular grid which consists of planar curves with various curvatures (Figure 4). The primary structure consists of 12 laths (a–l) with single-signed curvatures and the 8 laths (1–8) of the secondary structure have double-signed curvatures with up to two inflection points.

Subsequently, the aforementioned planar curves were given to an algorithm (as described above) which calculates the

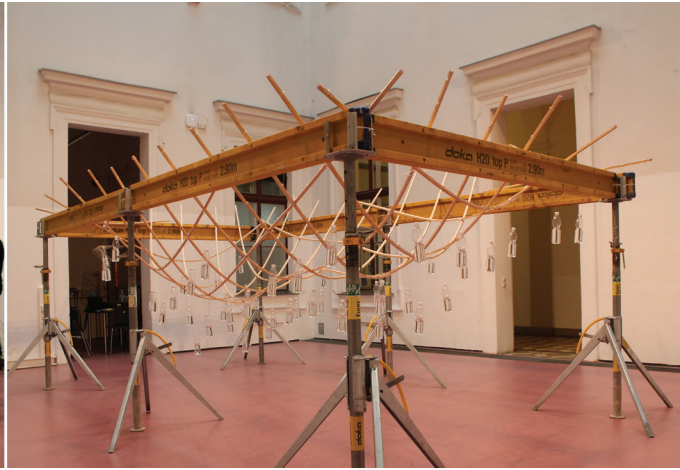
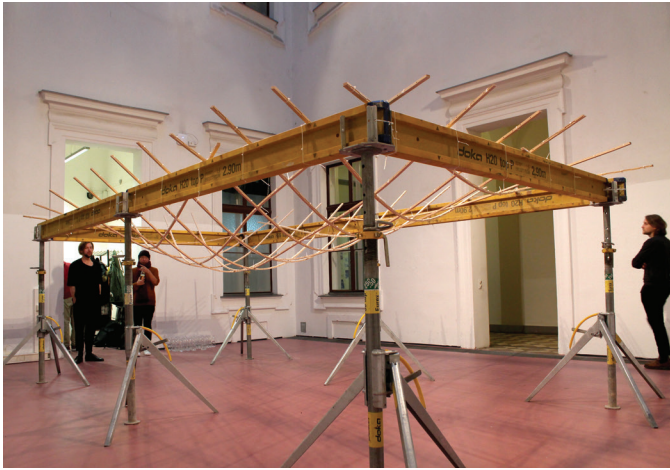
appropriate gap lengths along the linear elements. This leads to the design of flat double-layered notched laths which are deformed to the predefined shape when loads are induced. For the single-signed curves, the locking point between the layers was inserted at one of their ends. For the curves with one inflection point, the locking point was placed where the sign of the curvature changes. Finally, the curves with two inflection points were left flexible in their middle to deform while being supported by the primary structure.

The cross section dimensions of the double-layered laths are 15 x 20 mm (5 mm gap height) which is due to the minimum radius of curvature of the design ( $r=1.4$  m). The laths are made of white ash and due to the slenderness of their parts and the fabrication precision needed, robotic CNC milling was selected as a fabrication method. With a 6 mm milling bit and a pneumatic clamping mechanism mounted on the wall, each linear element (max 3 m long) was fabricated in 7 minutes (Figure 5). This resulted in a fabrication time of approximately 4 hours. A tolerance of 1 mm was given to the notched geometries, and small fabrication imprecisions (0.5 mm) were created by the vibration of the robot when cantilevering. The laths that were longer than 3 m were glued via diagonal shifters. Finally, the two layers of each lath were joined together with zip ties.

For the assembly of the structure, the elements were placed on a DOKA frame so that both of their ends were free to slide. The primary structure was placed first and then the secondary. Subsequently, loose zip ties were put around the nodes of the gridshell as a quick joint that allowed sliding between the primary and the secondary structure. When equal loads of 5 N were hung from each node, the grid formed a double-curved shape (Figure 6). The resulting shape relies on the variable internal geometry of each double-layered lath which defines its maximum deformation and consequently the global deformation of the gridshell. The installation process was uncomplicated and quick.

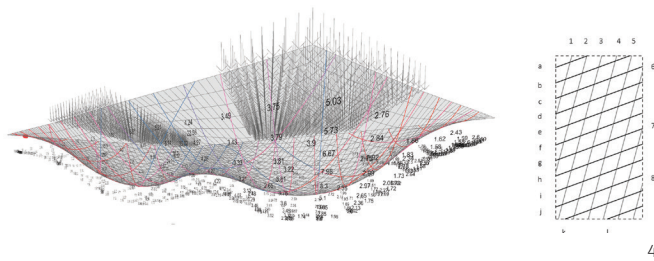
### Cantilevering Gridshell

The second prototype refers to a cantilevering gridshell structure (5 x 4 m footprint). It consists of five (1–5) double-layered beams in the primary direction and four (a–d) in the secondary. Spruce GL24 was chosen for the materialization of the beams as it is broadly used in the construction industry. In addition, the cross section of each double-layered beam was decided to be 60 x 60 mm due to fabrication constraints. The ‘tooth’ height was 1/3 of the beam height and its length (180 mm) was constrained to the width of the clamping mechanism of the CNC machine. Each beam of the primary structure has been designed to have constant curvature. However, its 5 beams exhibit different

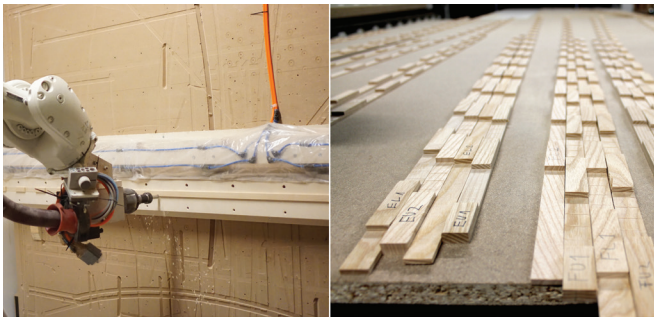


7

6 Suspended gridshell. Left: Dead loads, Right: Gravitational loads applied at all the nodes.



4



5

4 Left: Suspended gridshell designed by form-finding process. The colors and numbers represent the curvature values along the laths. Right: Plan view with numbered elements.

5 Robotic fabrication and resulting timber lath layers.

curvatures, decreasing gradually from beam 1 ( $r=7.6$  m) to beam 5 ( $r=60$  m). The primary structure defines the deformation of the gridshell, while the secondary, perpendicular to the first one, follows the curvature of the primary structure (Figure 7).

One of the aims of this prototype was the industrial fabrication of the notched beam layers. Thus, Hundegger K3 was chosen as an industrial CNC milling machine optimized for rapidly machining joinery details of long, flat timber beams. Considering that standard beams used in the construction industry have few joints and larger cross sections than the layers of the proposed variable stiffness beams, the

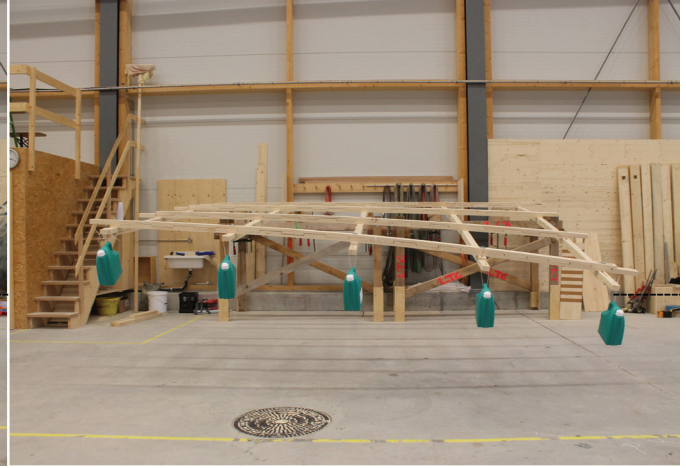
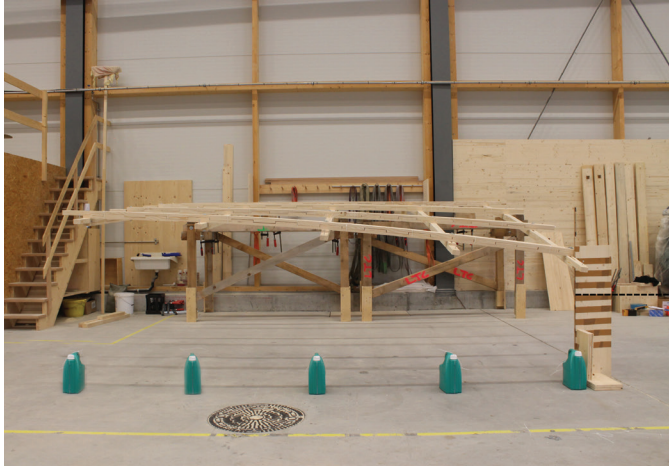
fabrication of these beams was challenging.

The first fabrication test was conducted for single layers of beams (Spruce C24 40 x 60 mm) 5 m long which were machined from the bottom. Due to their small cross sections, the clamping mechanism of the K3 was unable to hold them still. On top of that, their lightness allowed high vibrations during the machining of the ends of the beams, which led to breakages. As a result, the milled pieces had rough finishing and imprecisions of the scale of centimeters (Figure 8 left).

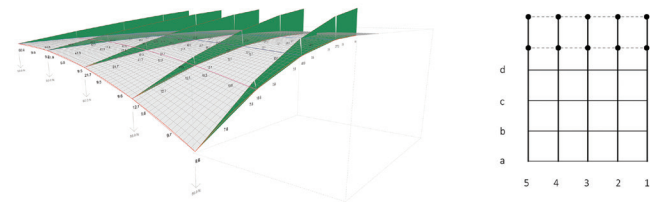
Due to the unsatisfactory results of the abovementioned fabrication test, a second one was conducted. The intention was to increase the weight of the milled beams and thus minimize the vibrations. The two layers of each double beam were milled back to back out of a single glue-laminated beam (Spruce GL 24) of a bigger cross section (60 x 100 mm). The 'teeth' of the two layers were aligned in order to offer a strong grip to the pneumatic clamping mechanism of K3. Thus, the latter could tightly grasp the beams from their full cross section width (100 mm) and slide them along the rail of K3, where they were milled simultaneously on both sides. The fabrication ran without problems and the resulting beams had a good finish (Figure 8 right). The 1.5 mm tolerance that was given to the fabricated pieces proved adequate for the given machine. The fabrication time of each double-layered beam took approximately 19 minutes. Consequently, the milling of all the elements lasted 3 hours. Finally, the beams were sliced along their longitudinal axis with an electric saw so as to separate the upper from the lower layer. The layers were joined together with zip ties.

During the assembly, the cantilevering beams were mounted on a fixed base, and subsequently the secondary beams were placed on top. The installation was simple and completed by 2 people in a couple of hours. When loads





9 Cantilevering gridshell. Left: Dead loads, Right: Gravitational loads applied at the five cantilevering tips.



7 Cantilevering gridshell. Left: Perspective view showing the radius of curvature of the beams and the moments (green) of the primary structure, Right: Plan view with numbered elements.

8 From left to right: Evolution of milling quality with Hundegger K3.

of 50 N were added at the ends of the primary structure, the gridshell formed a double curved surface (Figure 9). Despite the fact that all the beams of the primary structure had the same cross section and the same loading, beam 5 had short gaps between its layers, allowing small slip and thus small deflection (stiffest beam). On the contrary, beam 1 had longer gaps and thus allowed bigger slip and larger deflection (most flexible beam).

## RESULTS FROM PHYSICAL PROTOTYPES

The aforementioned prototypes were the first experiments to prove that the described geometry-induced variable-stiffness beams can be used for the self-formation of gridshells. In the previous section, it was made clear that there is a qualitative correspondence between the predefined form and the resulting geometry (Figures 6 and 9). However, the detailed comparison between the initially designed curves and their physical form has been

considered as a crucial step to evaluate the performance of the system. The quantitative results are described in the following sections for both the suspended and the cantilevering gridshell.

### Geometrical Evaluation of Suspended Gridshell

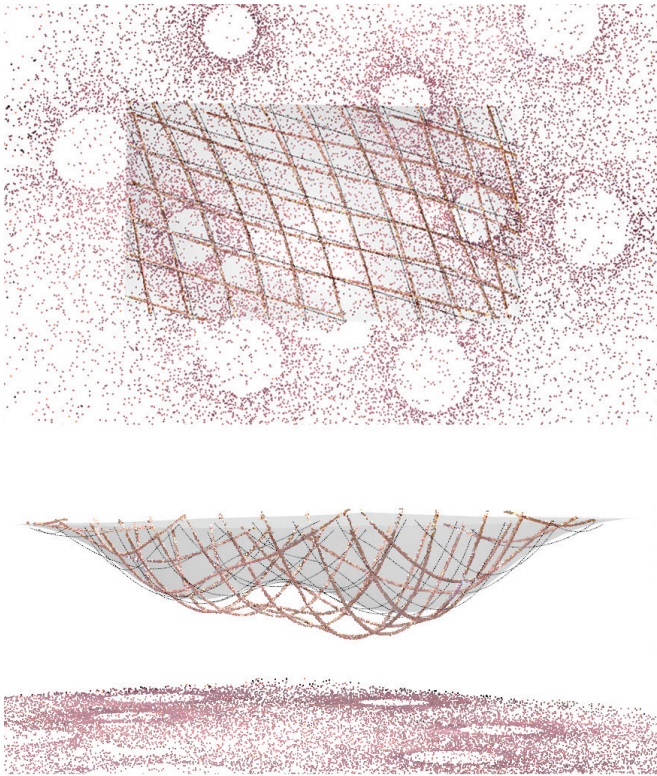
The physical form of the suspended gridshell was extracted from a point cloud collected by a laser 3D scanner. Juxtaposing the point cloud over the digital design showed that the physical form has a maximum deviation of 340 mm in the middle of the structure (Figure 10 bottom). Additional small deviations of maximum 100 mm have been noticed in the xy plane (Figure 10 top).

A comparison between the physical and the digital form of every single double-layered lath shows their exact deviation (Figure 11). As mentioned before, larger deviations have been noticed at the middle laths of the primary structure (e–h) and at the laths with two inflection points of the secondary structure (3–5). Despite the fact that the laths with two inflection points showed double signed curvature in their physical form, the magnitude of the resulting curvature was decreased and mainly induced by the primary structure.

For comparison purposes, the aforementioned gridshell has been structurally analyzed as though it consisted of single solid rectangular laths ( $h=8.2$  mm) with equal bending stiffness as the flat double-layered notched laths. Considering the same boundary conditions, figure 12 shows that the deflection of the hypothetical structure resembles, as expected, a catenary form with the maximum deflection at the middle.

### Geometrical Evaluation of Cantilevering Gridshell

The comparison between the physical and the digital form of the cantilevering gridshell focuses more on the shape of the



11. Comparison between the 3D scan of the suspended gridshell (brown) and the digitally designed form (grey/black). Top: Top view, Bottom: Perspective view.

primary structure. While beam 1 shows a smaller maximum deflection than the predefined curve, the beams 3, 4 and 5 show bigger deflections than initially planned (Figure 13). Examining the radii of curvature of the primary beams (1-5), it was noticed that whereas the predefined curves have constant curvature, the resulting curves have decreasing curvature towards their tip. This curvature is similar to the curvature induced to a standard cantilevering beam by a point load at its tip (maximum curvature at the support to 0 curvature at the tip).

Finally, for verifying the controlled stiffness of the notched beams, the cantilevering gridshell has been structurally analyzed as though it consisted of single solid laths ( $h=32$  mm) with equal bending stiffness as the flat double-layered notched laths. Considering the same boundary conditions, the analysis showed that the deflection of the hypothetical gridshell is larger than the physical result of the experiment (Figure 14). Consequently, it is proven that as the gaps between the shear blocks decrease, the stiffness of the elements increases. Experimental data of beam 2 showed that its stiffness increased 1.8 times during its deformation (Baseta et al. 2018). Thus, the element is able to block before it reaches the maximum deflection of its layers.

## Discussion

The qualitative and quantitative comparison between the physical and the digital form of the aforementioned prototypes brings valuable insights for the further development of the presented self-formation process. Both prototypes showed similar deficiencies which are summarized below.

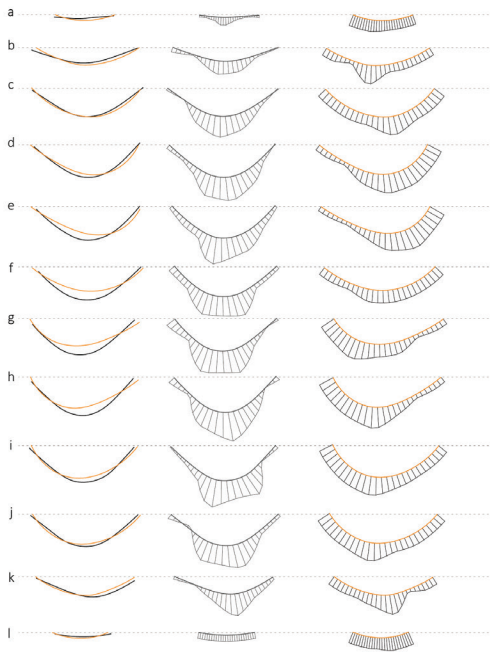
Firstly, inaccuracies in the resulting curvature of the individual elements have been noticed. This is partly due to the fabrication tolerances since 1 mm increase of the gap length results in deviations of several centimeters (e.g. 130 mm for the elements of the suspended prototype). As a result, further fabrication tests need to be conducted to achieve a precision of 1/10 of a millimeter. An additional reason for the curvature inaccuracy was the elasticity of the notched joinery detail. This led to a lower resulting stiffness of the elements and thus bigger deflections. Therefore, finite element analysis (FEA) for strengthening the joinery detail should be conducted.

Secondly, the difficulty of sliding between the primary and the secondary structure led to a constrained deformation of the system. The increased friction at the nodes of the gridshell was caused by the transversal torsion induced during the deformation. This is particularly visible in the plan view of the suspended structure, where the elements do not remain planar. Thus, further tests with industrial or custom joinery details of the nodes should be conducted. Finally, for the presented prototypes, wood has been used as a flexible and strong material which can be easily machined. Timber fulfills the material properties required from the functionality of the described prototypes. In addition, it constitutes a cost-effective fabrication solution. However, future experiments may include materials with high strength to stiffness ratio, such as fiber reinforced polymers. As a result, broader possibilities of fabrication strategies and joinery details can lead to a system with improved performance.

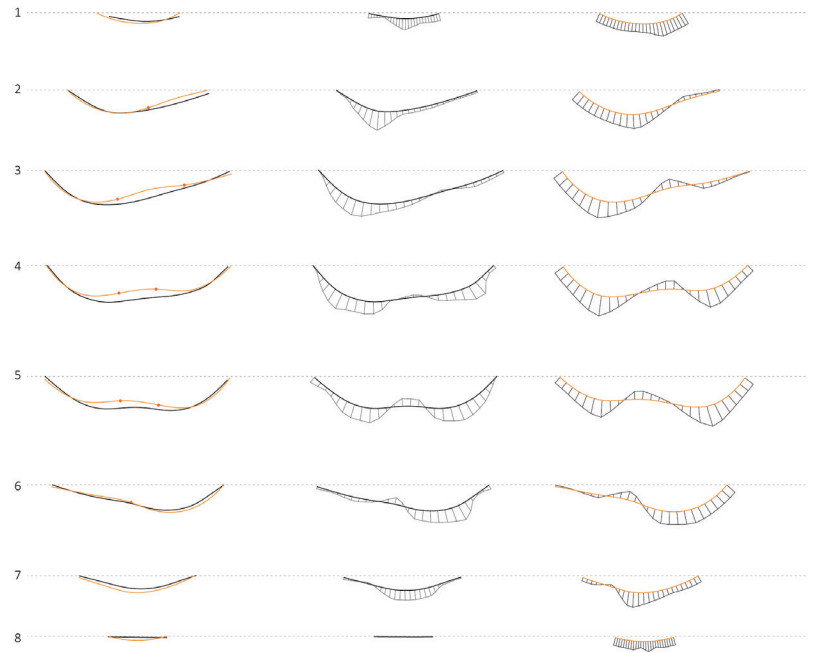
## CONCLUSION

The proposed geometry-induced, variable stiffness elements show potential for application in the self-formation of gridshell structures. The joinery details between the double-layered beams act like an embedded construction manual. Thus, digitally designed double curved surfaces can be easily and rapidly constructed through controlled active bending. The two examined experimental prototypes proved the qualitative correspondence between the digital and the resulting physical form, while quantitative tolerances need to be explored further. Thus, additional fabrication tests, as well as finite element analysis and digital simulations of the system need to be conducted. The ability to fabricate the

Primary structure

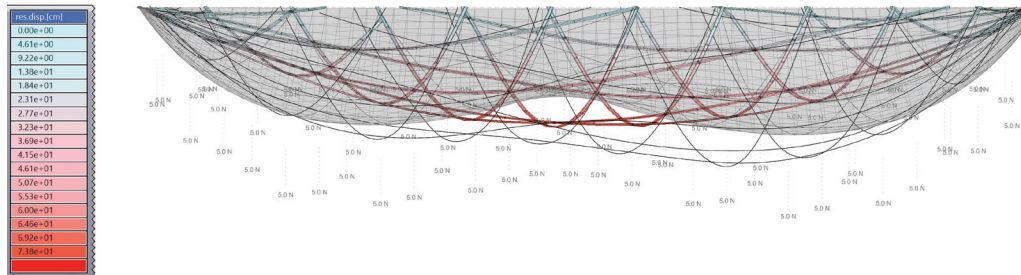


Secondary structure



12

12 Comparison between the curvature of digital (orange) and physical (black) elements of the suspended gridshell.



13 Colored laths: Deformation of a hypothetical gridshell which consists of rectangular single laths (cross section: 8.2 x 20 mm) with 5 N point loads at every node. Black lines: Physical form of the prototype, Grey mesh: Predefined digital shape.

13

variable stiffness elements with industrial machines shows great potential in scaling-up the system. Nevertheless, further physical experiments in larger scale need to be conducted to prove its structural performance. When the self-formation is reversible, the presented system can find applications in passive transformable structures.

## ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 642877.

The fabrication and installation of the cantilevered prototype would not have been possible without the support from the Blumer Lehmann AG (Gossau, Switzerland) team and its leaders Kai Strehlke and Martin Antemann.

The design, fabrication and installation of the suspended prototype was part of the course 'Digital Design and Full Scale Fabrication '17' in the University of Applied Arts Vienna-Institute

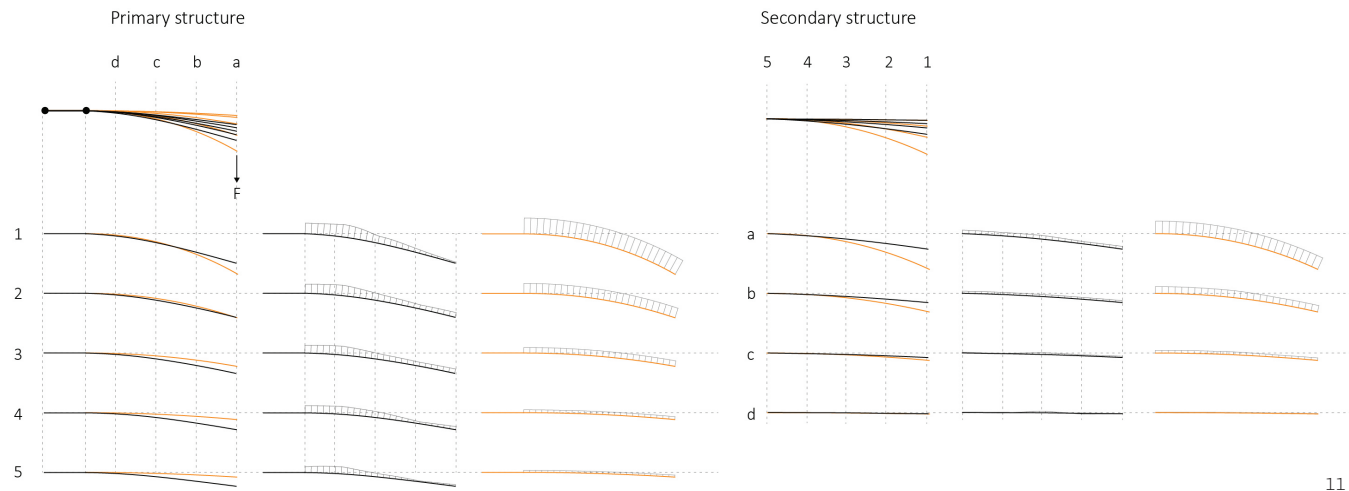
of Architecture led by Andrei Gheorge. Philipp Hornung representing the Angewandte Robotic Lab and the Wood technology laboratory led the robotic fabrication. Students of the course: Adrian Herk, Afshin Koupaei, Aleksandra Belitskaja, Alex Ahmad, Alexandra Moisi, Andrej Strieženec, Anna Tuzova, Ben James, Charlotte Krause, David Rüßkamp, Jan Kovářčěk, Jelinek Johanna, Jonghoon Kim, Julian Heinen, Kaspar Ehrhardt, Leonie Eitzenberger, Ludmila Janigova, Madeleine Malle, Michael Tingen, Minhong, Polina Korochkova, Rudolf Neumerkel, Sadi Özdemir, Shaun McCallum, Toms Kampars, Zarina Belousova.

## REFERENCES

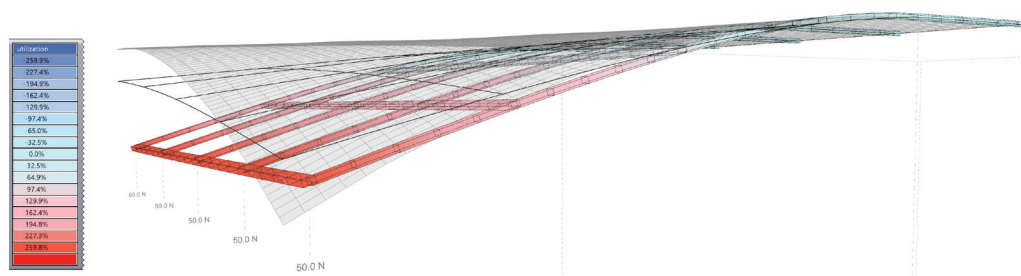
Alexander, Christopher. 1964. *Notes on the Synthesis of Form*. Cambridge MA: Harvard University Press.

Alquist, Sean. 2015. "Social Sensory Architectures: Articulating Textile Hybrid Structures for Multi-Sensory Responsiveness and Collaborative Play." In *Computational Ecologies: Design in the Anthropocene, Proceedings of the 35th Annual Conference of the*





11 Comparison between the curvature of digital (orange) and physical elements of the cantilevering gridshell.



12 Colored laths: Deformation of a hypothetical gridshell which consists of rectangular single laths (cross section: 32 x 60 mm). With 50 N point loads at every cantilevering tip. Black lines: Physical form of the prototype, Grey mesh: Predefined digital shape.

12

Association for Computer Aided Design in Architecture, edited by L. Combs and C. Perry, 263–73. Cincinnati, OH: ACADIA.

Baseta, Efilena, Clemens Preisinger, Martin Antemann, Kai Strehlke, and Klaus Bollinger. 2018. "Geometry-induced variable stiffness structures." In *Creativity in Structural Design: Symposium of the International Association for Shell and Spatial Structures 2018*, edited by C. Mueller and S. Adriaenssens, Boston: IASS.

Burgert, Ingo, and Peter Franzl. 2009. "Actuation systems in plants as prototypes for bioinspired devices." *Philosophical transactions. Series A, Mathematical, Physical, and Engineering Sciences* 367 (1893): 1541–57.

Frazer, John. 1995. *An Evolutionary Architecture*. London: Architectural Association.

Gengnagel, Christoph, Holger Alpermann, and Elisa Lafuente. 2013. "Active Bending in Hybrid Structures." In *Form–Rule | Rule–Form 2013*, edited by Günther H. Filz, Rupert Maleczek, and Christian Scheiber, 12–27. Innsbruck: Innsbruck University Press.

Knippers, Jan, Klaus Nickel, Thomas Speck. 2016. *Biomimetic Research for Architecture and Building Construction: Biological Design and Integrative Structures*. Switzerland: Springer.

Körner, Axel; Madar, Anja; Saffarian, Saman and Knippers, Jan. 2016. "Bio-Inspired Kinetic Curved-Line Folding for Architectural Applications." *Posthuman Frontiers: Data, Designers, and Cognitive Machines, Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by K. Velikov, S. Ahlquist, M. del Campo, and G. Thün, 270–9. Ann Arbor: ACADIA.

Kotelnikova-Weiler, Natalia, Cyril Douthe, Elisa Lafuente, Olivier Baverel, Christoph Gengnagel, and Jean-François Caron. 2013. "Materials for Actively-Bent Structures." *Space Structures* 28 (3–4): 229–40.

Liddell, Ian. 2015. "Frei Otto and the Development of Gridshells." *Case Studies in Structural Engineering* 4: 39–49.

Lienhard, Julian, Holger Alpermann, Christoph Gengnagel, and Jan Knippers. 2013. "Active Bending, A Review on Structures where Bending is used as a Self-Formation Process." *Space Structures* 28 (3–4): 187–196.

Lienhard, Julian, Sean Alquist, Achim Menges, and Jan Knippers. 2013. "Extending the functional and formal vocabulary of tensile membrane structures through the interaction with bending-active elements." In *[Re]Thinking Lightweight Structures: Proceedings of TensiNet Symposium*, 109–18. Istanbul: TensiNet.

Lienhard, Julian, and Jan Knippers. 2015. "Bending-Active Textile Hybrids." *International Association for Shell and Spatial Structures* 56: 37–48.

Lienhard, Julian, and Jan Knippers. 2013. "Considerations on the Scaling of Bending-Active Structures." *Space Structures* 28 (3–4): 137–148.

Sparrman, Bjorn, Chris Matthews, Schendy Kernizan, Aran Chadwick, Neil Thomas, Jared Laucks, and Skylar Tibbits. 2017. "Large-Scale Lightweight Transformable Structures." In *Disciplines & Disruption: Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture*, edited by T. Nagakura, S. Tibbits, M. Ibanez, and C. Mueller, 572–81. Cambridge, MA: ACADIA.

## IMAGE CREDITS

All other drawings and images by the authors.

---

**Efilena Baseta** is an architect engineer, studied in the National Technical University of Athens (NTUA), with a Master degree in Advanced Architecture from the Institute for Advanced Architecture of Catalonia (IAAC). Her interest lies in exploring material behaviors, physically and digitally, in order to develop novel structural systems. Since 2014 Efilena is a co-founding partner of Noumena, a multidisciplinary practice developing innovative solutions based in Barcelona. She has led several workshops internationally and also has been part of the design and coordination of exhibitions related with technology. During 2015-2016 she collaborated with IAAC as the coordinator of the Visiting Programs and tutor of the Global Summer School 2016. Efilena is currently a Marie-Curie researcher at the University of Applied Arts Vienna on the topic of transformable structures.

---

**Klaus Bollinger** has studied Civil Engineering at the Technical University Darmstadt and taught at Dortmund University. Since 1994 he has been assigned Professor for Structural Engineering at the School of Architecture/University of Applied Arts at Vienna. In 1983 Klaus Bollinger and Manfred Grohmann established the practice Bollinger + Grohmann, now located in Frankfurt am Main, Vienna, Paris, Oslo and Melbourne with around 100 employees. The office provides a complete range of structural design services for clients and projects worldwide. Their scope of work includes building structures, facade design and building performance for commercial, retail and exhibition facilities as well as classic civil engineering structures such as bridges, roofs and towers.