IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

*Proceedings of the IASS Annual Symposium 2018*
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

# Recent developments in bending-active structures

Julian Lienhard*, Christoph Gengnagel[a]

*str.ucture GmbH, Stuttgart – lienhard@str-ucture.com
[a] Universität der Künste Berlin (UDK)

## Abstract

Active-bending was established as a new Study Group within the IASS Working Group 15, "Structural Morphology Group" (SMG) in 2012 at the IASS conference in Seoul. Starting point was the publishing of a review paper [1] to establish common terminologies and references. In this paper many important historical examples of active-bending were gathered, dating back as far as early Mesopotamian dwellings up to the comparatively few contemporary examples of bending-active structures existing at that moment.

Since the founding of the study group the community of researchers as well as practicing architects and engineers has rapidly grown and managed to establish the subject within multiple simulation software, many realized prototypes and some commercial building structures.

The current paper highlights some recent developments in the field of active-bending. As part of an outlook, some future trends are discussed to critically highlight the potentials of using active-bending as a promising approach to novel hybrid building structures.

**Keywords:** bending-active, review, formfinding, hybrid structures

## 1. Introduction

Active-Bending is understood as an approach to generate curved structural form by means of elastic bending from initially straight or planar elements. Structures built on the basis of these principles are referred to as bending-active structures [2]. As such, bending-active structures do not describe a specific structural type, but rather an approach. Within this deliberately open definition some types of bending-active structures may be differentiated:

- Elastic Gridshells
- Bending Plate structures
- Textile Hybrids
- Elastic kinetic structures

While elastic grid-shells have been discussed within IASS ever since their first appearance in the 1960s, the other types have only few precursors. In recent years, and especially since the founding of the active-bending group within IASS, the community of researchers as well as practicing architects and engineers active in this field has rapidly grown and managed to establish the field of study through the development of several simulation software, many realized prototypes and some commercial building structures. In this short review some recent developments in the field of active-bending are highlighted.

## 2. Recent developments and applications

The following sections presents some recent developments in the field of active-bending, with the above introduced differentiation of types. Without the claim to be comprehensive the collection of projects highlights the current state of the art in bending-active structures.

### 2.1. New developments Grid shells

Elastic gridshells exhibit three unique characteristics: continuous and overlapping laths, the application of elastic bending to achieve single or doubly curved geometries and a rotational degree of freedom in the nodes normal to the shell surface during erection. These form-finding and erection methods make grid-shells fall under the definition of bending-active structures. Many material studies and the development of software tools in the field of grid-shells have heavily informed and influenced the research on bending-active structures in general.

After completion of the grid forming, stabilization of the squares is necessary in order to achieve shear stiffness in the surface and subsequently to lock the form and activate structural shell behavior. This can be achieved by the addition of a third layer of diagonal members which triangulate the grid or by crossed cable elements in tension. Changing the node from pinned to rigid after forming also offers a method of form stabilization. However, this is at the cost of increased bending stresses in the members which are already limited in bending stiffness by design. A further option is the use of a membrane or other structural surfaces as a form of stabilizing element. Whilst the simulation and construction of elastic gridshells has been mastered over the years, the question of a structurally functioning and fast to install bracing system is still discussed in current research [3].

Depending on whether the edge length of the mesh is constant or variable, one differentiates between regular and irregular grid shells. In combination with the rotational freedom at the pinned nodes, a curved regular grid is able to be fully developed onto a flat plane. This makes it possible to assemble the structure fully as a flat grid prior to erection. An irregular grid shell on the other hand necessitates a partly or fully incremental assembly of individual members. Irregular grid shells can therefore be designed to avoid laths with excessive curvatures or to adapt mesh density to internal forces in the members. The research by Quinn [4] has studied erection methods based on pneumatic systems, tracing the development of bending forces during erection (Figure 1 dc).

Recent research has targeted the development methods to define grid topologies, which allow for integrated structural optimization and hence overcome the limitations of the traditional compass method. One example of a new method is the so called Variational Principles Method by Hernández et.al. [5], which offers significant improvements by its ability to reduce peak curvatures and subsequent residual stresses in the laths. Similar questions were studied by L. Bouhaya [6] using genetic algorithms.

Recent projects have also explored further material and structural potentials of gridshells by using alternative and recyclable material for the laths. A highlight is the gridshell made of reclaimed skis [7] (Figure 1 b) and the recent spatial bamboo structures like ZCB Bamboo Pavilion [8] (Figure 1 e) and the Pantographic Bamboo Hybrid Amphitheater Structure [9]. The inside out pavilion by Schling et.al. [10] expands the gridshell typology towards a system of laths which follow asymptotic curves and therefore only elastically bent around the weak axis in combination with torsion (Figure 1 f).

Reviewing the recent developments in bending-active structures it can be concluded that grid-shells are the only application of active-bending where large span efficient structures are possible. The hanging gridshell at La Closca demonstrates the potential of large span temporary structures [11]. The Cathédrale éphémère de Créteil highlighted the potential of gridshells as economic large span and permanent structures [12]. The remaining challenge however lies in the development of structurally active covering and cladding systems.

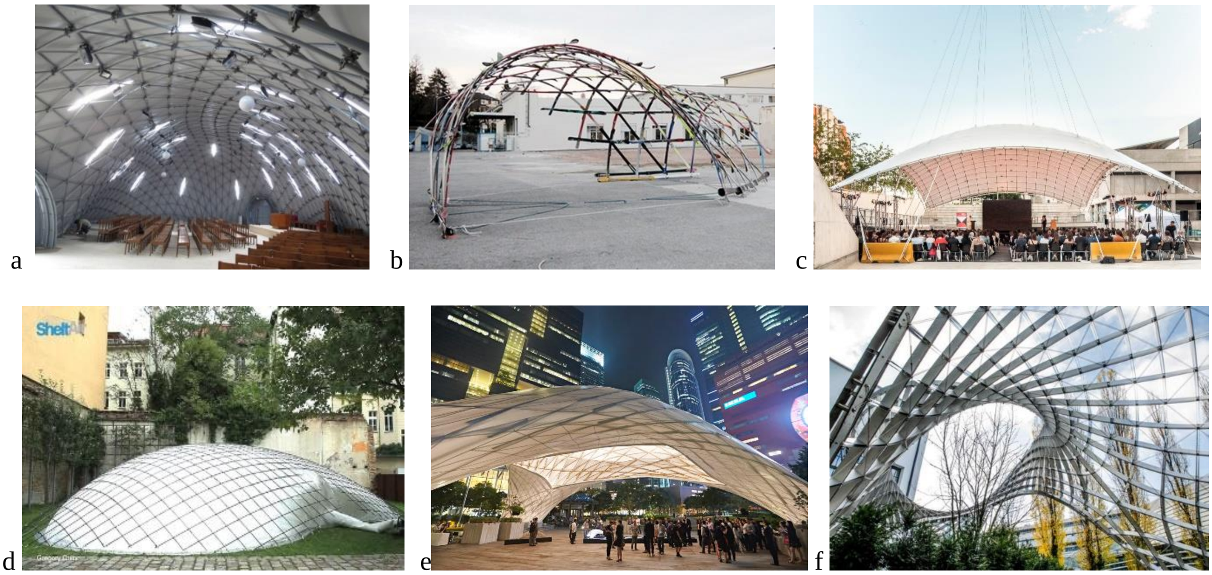


Figure 1: Recent Gridshell projects: a: Cathédrale éphémère de Créteil 2017 [12], b: Elastic Gridshell out of Reclaimed Skis 2017 [7], c: La Closca 2017 [11], d: SheltAir 2017 [4], e: ZCB Bamboo Pavilion 2017 [8] f: inside out 2017 [10]

## 2.2. Bending Plates

Double curved shell structures which achieve form and stability through the elastic deformation of thin plates are referred to as bending-active plate structures. Buckminster-Fuller's 1957 Plydome are still amongst the most prominent examples of such structures. However, due to the limitations of shear stiff plates to elastically bend into double curvature, bending-active plate structures have not received much attention and are generally considered difficult to design [13]. One reason is that plates have a limited formability since they deform mainly along the axis of weakest inertia and thus cannot be easily forced into more complex double curved geometries. Recent research and realized prototypes have been exploring the structural and form inducing potential of bending-active plate structures. The work by La Magna and Schleicher explores formfinding principles by placing voids in double curved surfaces to minimize double curvature in the elastically bent plates [13][14] (Figure 2 a and b). The possibility to assemble a larger structure from modular plate segments was realized with volumetric bent plate modules in the ICD/ITKE research pavilion 15/16 [15] (Figure 2 c).

The rapid assembly of bending-active plate structures and potential to explore spatial installations with simple means was demonstrated by the experimental pavilion by Soto at the University of Calgary [16] which was designed and built as part of the 'block-week' in a 3 day workshop period.

The work with elastically bent plates links the research on bending-active structures to curved line folding origami. Such origami principals have been used for elastic kinetic systems and also temporary installation like 'undulates' at IASS 2016 pavilion competition [17] (Figure 2 e).

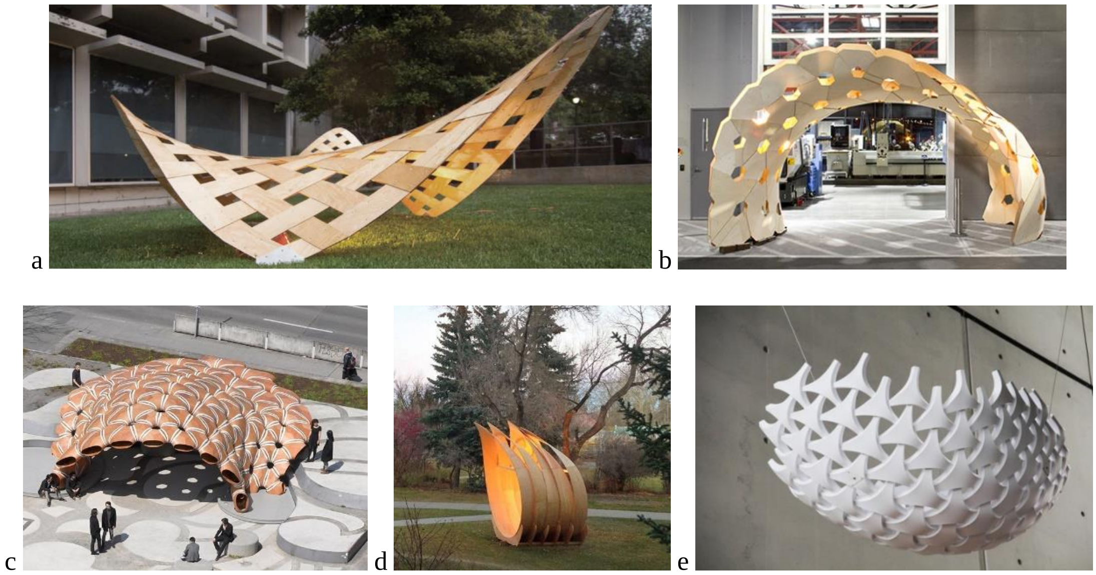


Figure 2: Recent bending-active plate projects: a: Berkeley Weave 2016 [13], b: Bend9 2016 [13], c: ICD/ITE Research pavilion 15/16 [15], d: experimental pavilion University of Calgary 2015 [16], e: undulates 2016 [17]

### 2.3. Textile hybrids

The interdependence of form and force of mechanically pre-stressed textile membranes and bending-active fibre-reinforced polymers has been established to be classified as a Textile Hybrid or more precisely Bending-Active Textile Hybrids (BAHS). The flexibility and lightness inherent to bending-active structures integrates well with the pre-stressed membrane structures which are flexible and adjust to applied loads. The particular reciprocal dependency between mechanical properties, pre-stress and form makes them a particularly interesting field of application for bending-active structures and consequently led to many built prototypes and structures in the recent years. Functionally, the integration of elastic beams within a pre-stressed membrane surface offers the possibility of short-cutting tension forces and creating free corner points. The system is stabilized solely by the elastic beams which, in turn, are restrained by the membrane surface. Since buckling of the beam is prevented, slender profiles may be used. The combination of pre-stressed membranes with elastically deformed beams furthermore offers advantages in the homogeneous utilization of the beam’s cross-section. Without the pre-stressing of the membrane, the elastic beam will assume a parabolic shape where the end segments are straightened out and the apex is bent into a tighter radius of curvature. Set into an interactive equilibrium with the pre-stressed membrane, there can be substantially less variation in curvature of the elastic beam.

The form-finding challenge in equilibrating tensile surfaces with elastically bent elements has led to numerous software developments and design strategies some of which are discussed in a separate paper [18]. A particularly challenging form-finding question is found in the design of BAHS with open ended bending elements. The lack of restraining in such systems makes is particularly challenging to match the built geometry with the computational model. Such systems were built during the textile hybrid workshop 333 at CCA [19] (Figure 3 a), the textile Hybrid installation at HCU Hamburg [20] (Figure 3 b) and most recently at the Danish pavilion ‘Isoropia’ of the 2018 Venice Biennale [23] (Figure 3f).

The large scale Hybrid Tower takes a modular approach to compose a structural system of intersecting bending-active loops which is three dimensionally restrained by a knitted textile [20] (Figure 3 b). On a smaller scale textile hybrids have been built as sculptural prototypes as proof on concept for formfinding strategies such as the Physical Costa Surface [28] and several installations by Ahlquist [21] (Figure 3 c and e). Ahlquist has developed this work further into interactive play scapes which lead to a study of increasing stiffness and robustness of the bending-active structure in order to safely carry dynamic life loads [22].

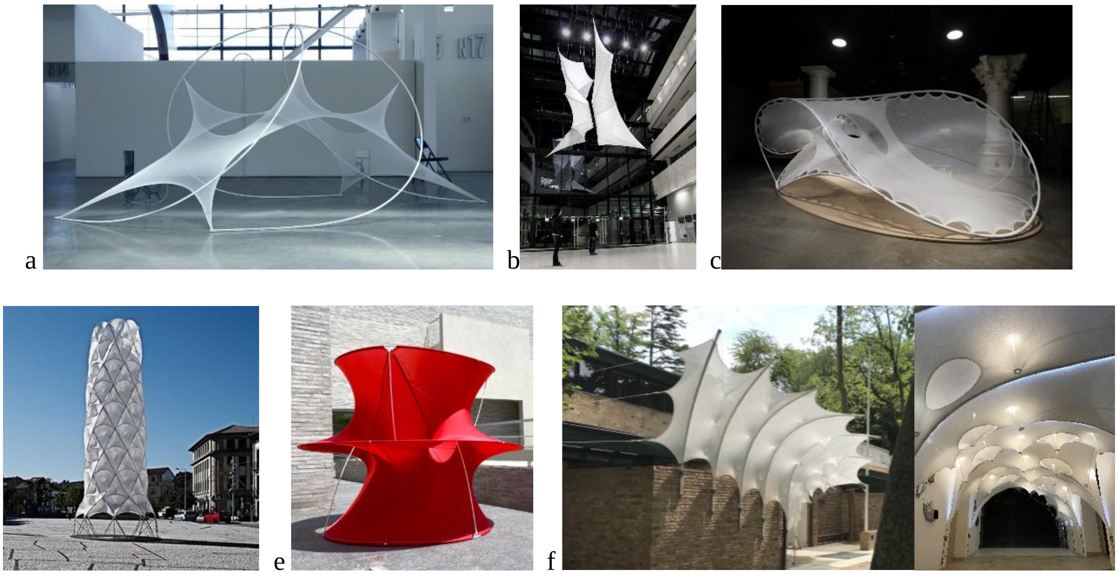

Figure 3: Recent textile Hybrid Projects: a: Installation at the 333 Workshop CCA 2015 [19], b: Textile Hybrid HCU Hamburg 2017 [20], c: stretch/play 2016 [21], d: Hybrid tower 2017 [23], e: Physical Costa Surface [28] f: 'Isoropia' at the Venice Biennale 2018 [24]

The research on textile hybrids has also led to a new interest in industrially knitted fabrics. Especially for smaller installations knitted fabrics, provide the opportunity of integrating details and tailoring material behavior. These potentials have been explored particularly in the research by Ahlquist, recently leading to the development of elastic play scapes [21] (Figure 3 c) and the work at CITA Copenhagen with the realization of a hybrid tower [23] (Figure 3 e) and the 'Isoropia' Pavilion 2018 [24] (Figure 3f).

## 2.4 Adaptive, elastic kinetic

A high potential of application of active-bending has developed around the exploration of elastic kinetics on an architectural scale. There is no other approach that offers so imminently the prospect of adaptation without any addition of supplementary mechanisms to the structure. Large scale realized projects like the 2012 Expo Korea façade and the Softhouse facade for the IBA 2012 Hamburg could already prove that bending-active structures can withstand the reality test even in locations of extreme wind occurrences. The work on elastic shape adaptation leads to further possibilities of including auxiliary functions in the structural elements. Current research on pneumatic bending-actuators integrated into the fibre layup of bending-active elements, suggests new perspectives for autonomous shape adaptation and variable stiffness on the basis of material intelligence.

Ongoing research on the Flectofold system addresses design, actuation and material questions for elastic kinetic elements [25] (Figure 4 a). Similar shading elements on a modular scale, based on curved line origami logics were developed by Vergauwen [26] (Figure 4 b). Most research on elastic kinetics has been informed by the study of plant movements, their potentials in finding strategies to amplify kinematic behavior has recently been summarized by Charpentier et. al. [27].

The connection of textile hybrids and elastic kinetics was explored by Puystiens [29] (Figure 4 d), focusing on the shape changing capacity of textiles during the form conversion of the kinetic systems. Aiming towards industrial applications, the principals of active-bending were integrated in large span furling sails, with an elastic central axis to enable the deployment of a doubly curved membrane from an initially straight axis [30] (Figure 4 e).

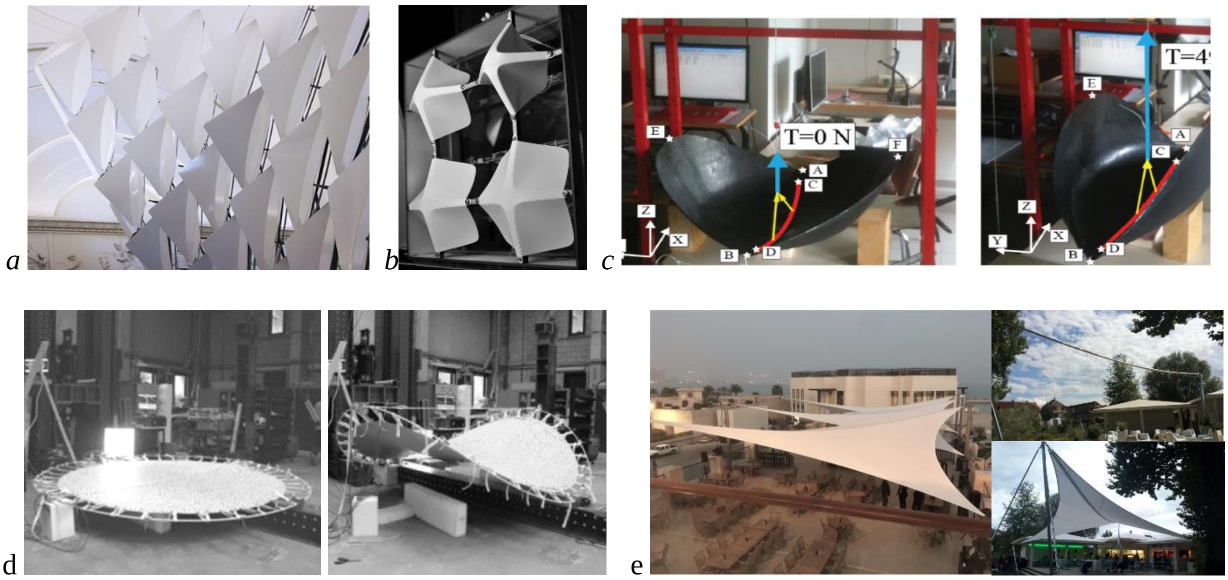


Figure 4: Recent elastic kinetic projects: a: flectofold [25], b: curved line folding [26], c: prototype of plants trap mechanism 2018 [28] e: d: research project VUB 2016 [29], 2: Bending-active furling sails 2015-2018 [30]

## 3. Conclusion

This short review shows that the activities around the subject of active-bending have drastically increased in recent years. Starting from an initially loose association of common interests, some clear fields of research and structural types were established. Whilst software to simulate bending-active systems was still rare at the time of the study group establishment in 2012, our computational means have advanced considerably since then. Today there are multiple integrated software tools on the basis of particle spring systems with dynamic relaxation solvers, the most prominent being Kangaroo 2 by Daniel Piker with a pipe line trimmed towards calibrated form finding of bending active systems by Quinn et al. [31]. Finite Element software like SOFiSTiK have been optimized towards faster and more integrated form-finding procedures with a most recent addition of an active-bending beam module which enables the formfinding and simulation of bending-active structures starting from curved input geometries and therefore providing a direct link to ‘pre-formfound’ exported geometries, for example from Kangaroo [32]. With the rapid development of Isogeoemtric Analysis there is also a most recent addition of a completely new approach to formfinding and simulating bending-active structures directly within the CAD definition of Splines and NURBS surfaces [33].

These software developments have been the vehicle for the growing community of researches in the field of active-bending with an impressive output of prototype and large scale structures, some of which were highlighted in the current paper. This development was predicted in the first review paper [1] on bending-active structures, where the novel computational means were seen as the starting point for new developments in this field.

Future research will concentrate on further exploring these potentials with an apparent tendency towards hybrid structures.

## References

[1] J. Lienhard, H. Alpermann, C. Gengnagel, J. Knippers, "Active Bending, a Review on structures where bending is used as a self formation process," in *International Journal of Space Structures*, vol. 28, no. 3-4, pp. 187-196, December 2013. DOI: 10.1260/0266-3511.28.3-4.187

[2] Lienhard, J.: "Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein". *Dissertation, Universität Stuttgart,* Institut für Tragkonstruktionen und Konstruktives Entwerfen, 2014.

[3] P. Cuvilliers, C. Douthe, L.du Peloux, R. Le Roy, "Hybrid Structural Skin: Prototype of a GFRP Elastic Gridshell Braced by a Fiber-Reinforced Concrete Envelope," J*ournal of the International Association for Shell and Spatial Structures*, vol. 58 (2017), no. 1 March n. 191, pp. 65-78, March 2017. DOI: 10.20898/j.iass.2017.191.853

[4] G. Quinn, C. Gengnagel, K.-U. Bletzinger, "Simulating Pneumatic Erection of Strained Grid Shells via Dynamic Relaxation," in *Spatial Structures in the 21st Century: Proceedings of the IASS Annual Symposium 2016,* Tokyo

[5] E. L. Hernández, O. Baverel, C. Gengnagel, "On the Design and Construction of Elastic Gridshells with Irregular Meshes," *International Journal of Space Structures*, vol. 28, no. 3, pp. 161-174, Dezember 2013. DOI: 10.1260/0266-3511.28.3-4.161

[6] L. Bouhaya, O. Baverel, J. Caron, "Optimization of gridshell bar orientation using a simplified genetic approach" *Structural and Multidisciplinary Optimization*, vol. 50, no. 5, pp. 839-848, November 2014. DOI: 10.1007/s00158-014-1088-9

[7] Colabella, S., D'AMICO, B., HOXHA, E., & FIVET, C.: "Structural Design with Reclaimed Materials: an Elastic Gridshell out of Skis". *In Proceedings of the IASS Annual Symposium* 2017

[8] Crolla, K.: "Building indeterminacy modelling – the 'ZCB Bamboo Pavilion' as a case study on nonstandard construction from natural materials". *In Visualization in Engineering 2017*. DO - 10.1186/s40327-017-0051-4

[9] M. Seixas, J. Bina, P. Stoffel, J. Luiz Mendes Ripper, l. Eustáquio Moreira, K. Ghavami, "Active Bending and Tensile Pantographic Bamboo Hybrid Amphitheater Structure," *Journal of the International Association for Shell and Spatial Structures*, vol. 58 (2017), no. 3 September n. 193, October 2017. DOI: 10.20898/j.iass.2017.193.872

[10] E. Schling, D. Hitrec, R. Barthel, "Designing Grid Structures Using Asymptotic Curve Networks," in *Humanizing Digital Reality. Design Modelling Symposium Paris 2017*, Springer Nature, 2018, pp. 125–140. DOI: 10.1007/978-981-10-6611-5_12

[11] http://coda-office.com/work/LaClosca

[12] L. du Peloux, F. Tayeb, O. Baverel, J. Caron, "Construction of a Large Composite Gridshell Structure: A Lightweight Structure Made with Pultruded Glass Fibre Reinforced Polymer Tubes, *Structural Engineering International*, vol. 26 (2016), no. 2, pp. 160-167, May 2016. DOI: 10.2749/101686616X14555428758885

[13] S. Schleicher, R. La Magna, "Bending-active Plates: Form-finding and Form-conversion," in ACADIA2016, October 2016. [Online].

[14] R. La Magna, J. Knippers, "Tailoring the Bending Behaviour of Material Patterns for the Induction of Double Curvature," in *Humanizing Digital Reality. Design Modelling Symposium Paris 2017,* Springer Nature, 2018, pp. 441-452. DOI 10.1007/978-981-10-6611-5_3

[15] D. Sonntag, S. Bechert, J. Knippers, "Biomimetic timber shells made of bending-active segments," *International Journal of Space Structures*, vol. 32, no. 3-4, pp. 149-159, December 2017. DOI: 10.1177/0266351117746266

[16] https://www.designboom.com/architecture/university-of-calgary-evds-experimental-pavilion-block-week-11-07-2015/

[17] http://www.vub.ac.be/ARCH/ae-lab/projects/undulatus

[18] A. Bauer, P. Längst, R. La Magna, J. Lienhard, D. Piker, G. Quinn, C. Gengnagel, K. Bletzinger: "Exploring Software Approaches in Simulating Bending Active Systems" In: *Proceedings of the IASS Annual Symposium 2018*, Boston USA

[19] https://www.arch2o.com/333-summer-design-studio-at-cca-studio-ld/

[20] J. Lienhard, C. Bergmann, R. La Magna, J. Runberger, : “A Collaborative Model for the Design and Engineering of a Textile Hybrid Structure”. In: *Proceedings of the IASS Annual Symposium 2017*, 25-28 Sept. 2017, Hamburg, Germany
[21] S. Ahlquist, L. Ketcheson, C. Colombi, “Multisensory Architecture: The Dynamic Interplay of Environment, Movement and Social Function,” in *Architectural Design*, vol. 87, no. 2, pp. 90-99, March 2017. DOI: 10.1002/ad.2157
[22] S. Ahlquist, J. Lienhard: “Extending Geometric and Structural Capacities for Textile Hybrid Structures with Laminated GFRP Beams and CNC Knitting”. *In: Proceedings of the IASS Annual Symposium 2016*, Tokyo, Japan
[23] M. Thomsen, M. Tamke, A. Karmon, J. Underwood, C. Gengnagel, N. Stranghöner, J. Uhlemann, Jörg: Knit as bespoke material practice for architecture. *ACADIA 2016 Conference, POSTHUMAN FRONTIERS: Data, Designers and Cognitive Machines*, University of Michigan 2017
[24] R. La Magna, V. Fragkia, P. Längst, J., Lienhard, R. Noel, Y. Baranovskaya, M. Tamke, M. Ramsgard Thomsen: “Isoropia: an Encompassing Approach for the Design, Analysis and Form-Finding of Bending-Active Textile Hybrids” in: *Proceedings of the IASS Annual Symposium 2018*, Boston USA
[25] A. Körner, L. Born, A. Mader, R. Sachse, S. Saffarian, A. Westermeier, S. Poppinga, M. Bischoff, G. Gresser, M. Milwich, T. Speck, J. Knippers, “Flectofold – A biomimetic compliant shading device for complex free form facades,” *Smart Materials and Structures*, vol. 27, no. 017001, 10pp, November 2017. DOI: 10.1088/1361-665X/aa9c2f
[26] A. Vergauwen, L. De Laet, N. De Temmerman, "Computational modelling methods for pliable structures based on curved-line folding," *Computer-Aided Design*, vol. 83, pp. 51-63, November 2016. DOI: 10.1016/j.cad.2016.10.002
[27] Charpentier, V., Hannequart, P., Adriaenssens, S., Baverel, O., Viglino, E., & Eisenman, S. (2017). Kinematic amplification strategies in plants and engineering. *Smart Materials and Structures*, 26(6), 063002
[28] http://formfindinglab.princeton.edu/
[29] Puystiens, S., Van Craenenbroeck, M., Mollaert, M., Van Hemelrijck, D., De Laet, L. “Implementation of bending-active elements in kinematic form-active structures: Design of a representative case study”, *International Conference on Textile Composites and Inflatable Structures – Structural Membranes 2015*, Barcelona, Spain, 2015.
[30] www.str-ucture.com
[31] G. Quinn, A. H. Deleuran, D. Piker, C. Brandt-Olsen, M. Tamke, M. R. Thomsen, and C. Gengnagel, “Calibrated and Interactive Modelling of Form-Active Hybrid Structures,” in *Iass 2016 Tokyo Symposium*, 2016, pp. 1–9.
[32] J. Bellmann: “Active Bending starting on curved architectural shape” *VIII International Conference on Textile Composites and Inflatable Structures, Structural Membranes*, München 2017.
[33] P. Längst, A. M. Bauer, A. Michalski, and J. Lienhard, “Isogeometric Analysis for Modeling and Simulation of Building Processes,” in *Proceedings of the IASS Annual Symposium 2017 “Interfaces: architecture. engineering. science,”* 2017.