The 2021 World Congress on
Advances in Structural Engineering and Mechanics (ASEM21)
GECE, Seoul, Korea, August 23-26, 2021

Shape adaptation of a hybrid bending-active gridshell through cables activation

*Ioanna Anastasiadou[1)] and Marios C. Phocas[2)]

[1), 2)] *Department of Architecture, University of Cyprus, 1678 Nicosia, Cyprus*
[1)] *anastasiadou.ioanna@ucy.ac.cy*

ABSTRACT

Structures able to sustain multiple states of equilibrium through reversible elastic deformations are promising in the field of adaptive, lightweight architecture. Research and applications in the field prove that fiber-reinforced polymers (FRP) are well suited for shape transformations and deformations due to their large admissible strain and high stiffness. Along these lines, the present paper examines the deformation control and shape adaptation of a hybrid bending-active gridshell, assigned to glass fiber-reinforced polymer (GFRP). The proposed gridshell consists of four segments of elastic strips interconnected through controlled joints and a secondary system of struts and cable segments with variable length. The latter members enable adjustability of the system's form-found shape and deformation control. The three-stage development of the gridshell includes the planar deformation of the bending-active members (i), the erection of the system through continuous cables with variable length connecting the supports in span direction (ii), the reconfiguration of the system through the joints release and respective cable segments activation (iii). The numerical investigation of the gridshell is conducted through a progressive Finite-Element Analysis (FEA). Initial investigations conducted by the authors examined an alternative reconfiguration of the system emerging from a different scenario of cable segments activation. The current analysis aims at further addressing and evaluating the structure's transformation capabilities, form flexibility and adaptability.

1. INTRODUCTION

The importance of transformable, adaptable and sustainable architecture lies within aspects of the global humanitarian crisis. The specific field of study refers to fast assembly processes, lightweight construction and innovative materials in achieving structural transformations. Efficient kinematics rely on modification of geometrical system characteristics, handled through structural components that are interconnected in a specific way to transmit force and motion for a given performance (Phocas, Alexandrou

---

[1)] Ioanna Anastasiadou
[2)] Marios C. Phocas

and Athini 2019; Phocas, Christoforou and Matheou 2015). Rigid kinematic pairs in tensegrity and scissor-like structures allow for various shape adjustments. An alternative approach for inducing motion in structures is found in bending-active systems. In such systems, large deformations are utilized for form generation and self-stabilization (Lienhard 2014). Morphological adaptation is achieved through elastically deformable members with enhanced capabilities in their kinematics. Straight, planar elements gain double curved geometries through a deformation process, whereas the resulting system expresses an equilibrium between form, forces and material characteristics (La Magna 2017).

Historically, initial examples of bending-active structures are to be found in vernacular architecture. However, the work of Buckminster Fuller in the second half of the last century, gave the first insights in the possibilities of geometry driven shapes using elastic materials (La Magna 2017). The later work of Frei Otto in the early 60s introduced form-finding as a design tool and opened up a new spectrum of a material oriented approach in architecture. The Mannheim Multihalle, constructed in 1974 by Frei Otto and Buro Happold, was the very first elastic gridshell that was entirely form-found using hanging chain models (Liddell 2015). The example of the Mannheim gridshell revealed the potential of succeeding architectural qualities with considerable spans using elastically bent elements. Recently, new simulation strategies along with the availability of computational tools and new materials, enabled further investigation of new types of structures who gain their shape by means of elastic deformation of their members. Several research projects in the latest decade, investigated elastic gridshells, bending-active plate structures, textile hybrids and elastic kinetic structures (Lienhard and Gengnagel 2018).

A dominant factor considering the elastic members' transformation process, refers to the materials' properties, since the final geometry of the structure strongly depends on the material behavior during form-finding. In general, the higher is the residual stress after the form-finding process, the lower are the stress reserves under external loads. Suitable materials for bending-active structures are those with a low ratio of elastic modulus to bending strength. Timber has been mostly used in bending-active structures, such as in the Mannheim Multihalle, Weald and Downland and Savill Garden gridshells. However, for providing higher structural rigidity and global stability, often two profile layers in each grid direction are required in timber gridshells. Latest advanced manufacturing techniques enabled the production of fiber-reinforced polymers (FRP) materials with large admissible strain and higher stiffness (Kotelnikova *et al.* 2013). Related studies suggest that all fiber-reinforced composites offer a wide range of properties depending on the stiffness of the matrix and fibers (Gengnagel, Lafuente Hernández and Baumer 2013). Due to their higher ultimate strength properties and modulus of elasticity, FRPs' are able to provide higher rigidity to the structure, without the need of a second layer of profiles (Lafuente Hernández *et al*. 2012). However, in each material selection case, its long term behavior, in terms of creep and relaxation, shall be considered during design (Lafuente Hernández 2015). A recent experimental investigation of an elastic gridshell made of glass fiber-reinforced polymer (GFRP) tubes, under permanent bending stresses, confirmed the feasibility and durability of GFRP members. The specific experiment covered a time period of 6 years (Douthe and Stefanou 2021).

Bending-active structures with long spans may consist of elastic members with stiffening elements that form a hybrid structure with higher stiffness and rigidity (Gengnagel, Lafuente Hernández and Baumer 2013). In hybrid systems, different structural components are combined together in a way to develop a specific mechanical behavior in resisting forces, based on their different mechanical nature. For example, textile hybrid structures may refer to structural systems that combine bending-active elements with form-active membranes. Various built examples verified that the flexibility found in elastic members integrates well with membranes, resulting in promising lightweight structures, by means of structural performance and aesthetics. However, textile hybrids refer to passive structural systems, set into a static equilibrium. Alternatively, bending-active elements may also be combined with cable elements, that can be utilised both for a passive and active performance. The hybridization of elastic members with tension elements can improve the structural performance of the structure, whereas cable elements can also serve as actuation components for the erection process (Phocas and Alexandrou 2018). In this respect, cable elements may have a critical role in the design and structural performance of the system, as well as its adaptation potential by means of deformation control.

Along these lines, the present paper examines the shape adaptation of a hybrid bending-active gridshell, and its potential in succeeding form variation in multiple states of equilibrium. The shape adaptation of the hybrid gridshell is based on actively controlled cable segmentations. The gridshell's development follows three stages, i.e. planar deployment, vertical erection and system's reconfiguration. The latter is handled through the activation of controlled joints and respective cable segments.

2. HYBRID GRIDSHELL

The proposed gridshell consists of four segments of interconnected elastic GFRP strips in span direction. The system segments are interconnected in each strip by three controlled joints and a secondary system of struts and cable segments with variable length. Different configurations of the system can be reached depending on the joints' position. In the current scenario, two joints are placed at midlength of the strips between the second and third strut, whereas the third joint is placed at midspan, Fig. 1. The joint connections are actively controlled through electromagnetic brakes, acting as fixed connections during erection and moment free ones during reconfiguration of the system. By completion of the system's erection, the joints are released and specific cable segments are actuated in obtaining further target configurations. In the latter stage, the shape adaptation and stress-control of the hybrid gridshell are directly related to the length of the cable segments and the deformation behavior of the elastic members.

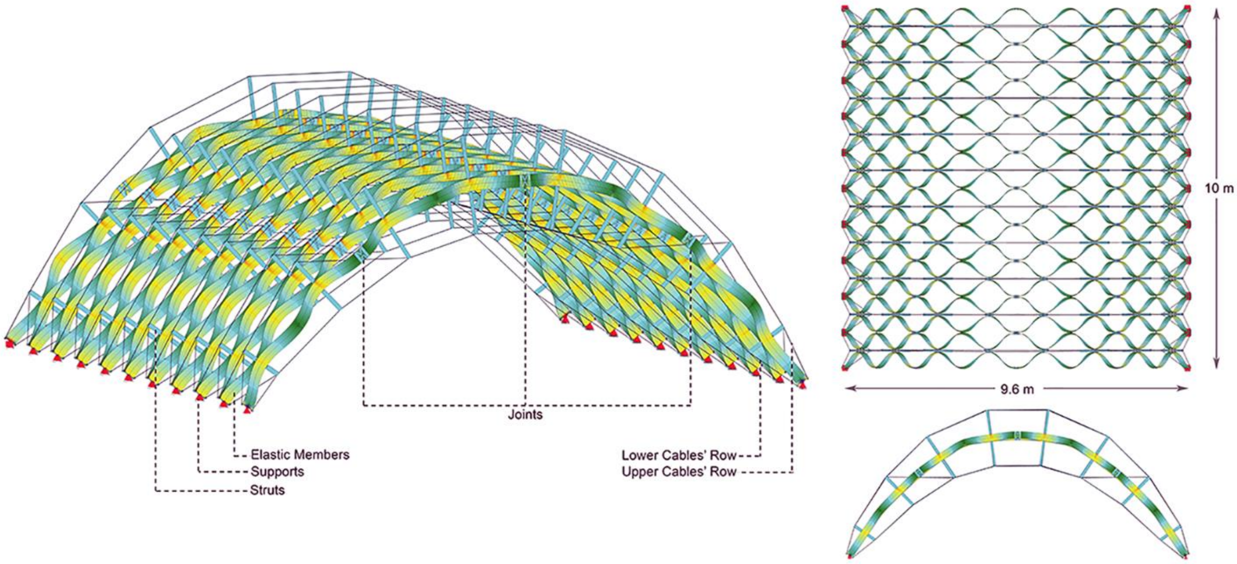

Fig. 1 Hybrid gridshell

3. GRIDSHELL DEVELOPMENT

The primary components of the hybrid gridshell comprise the elastic strips, mirrored to each other and placed with their strong axis aligned perpendicularly to the ground. The first stage of the analysis refers to the horizontal deployment of the structure, handled through an auxiliary set of cables. The cables' length reduction induces bending in the weak axis of the elastic members, enabling the deployment of the gridshell. The deployed grid has overall dimensions in its flat form of 12.4 x 10 m and 22 support points at the ends of the strips. Appropriate degrees of freedom were given to the ground supports, to enable the system to deploy and subsequently erect. Upon completion of the planar deployment of the gridshell, the system is erected through gradual shrinkage of continuous cables connecting the supports in span direction. The cables' shrinkage induces bending in the strong axis of the elastic members, lifting-up the structure. The erected target configuration of the structure has a span of 9.6 m and a length of 10 m. Following the vertical erection, cable segments connecting the upper and lower edges of the struts are applied. Subsequently, the internal joints of the system are released and specific cable segments of the upper and lower row are actuated, enabling the structure to reach further configurations, Fig. 2. The controlled joints allow rotations on the global Y-axis, in enabling the configurational transition of the system by activation and gradual shrinkage of the cables connecting the edges of the struts. Various scenarios of cables' actuation can be applied in achieving different configurations of the structure. Depending on the expected system reconfiguration, selected cables on the upper and lower row are actuated in achieving the respective target curvature at the gridshell's segments. The cables length reduction on the lower row forces the respective segments of the gridshell to move upwards, whereas the cables length reduction on the upper row, forces them to move downwards, providing the structure with a reverse curvature. Aesthetic, functional or structural demands can be taken into consideration when selecting each scenario of cables activation. The following case study seeks to provide a higher curvature near the supports, and a reverse curvature at the system's midspan. In order to reach this form, individual cables below and above the side joints and the middle joints of the system have been actuated. An alternative reconfiguration of the gridshell has been presented and analysed in (Anastasiadou and Phocas 2020). The target reconfiguration of the system is determined at the stage where the maximum stresses of the elastic members reach 90 % of the respective material's yield strength, i.e. 450 MPa, in preserving adequate stress reserves to the system, when further subjected to external loading. Once the reconfiguration stage of the system is completed, cables at the elements planes are added, running along the system span, in order to provide in-plane shear strength of the gridshell.

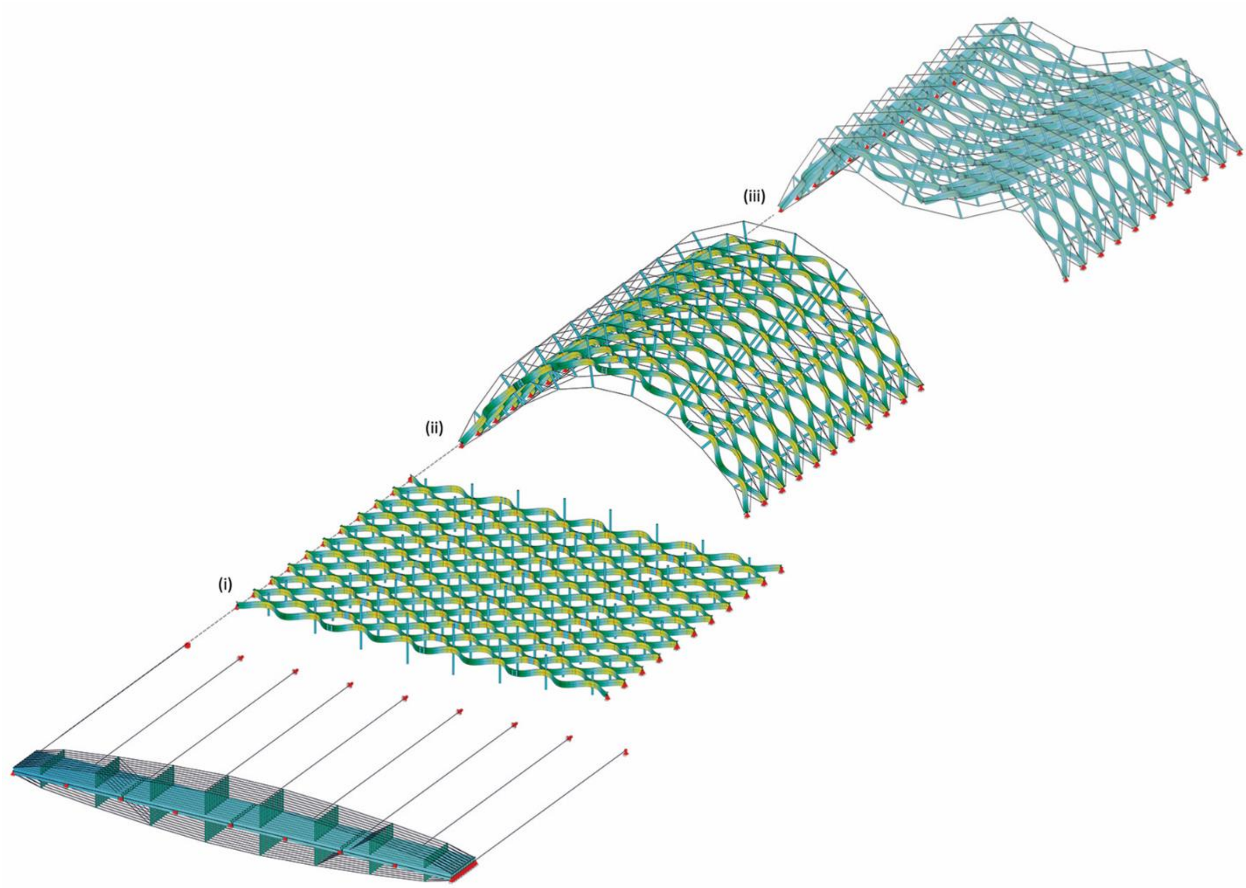

Fig. 2 System analysis stages; (i) planar deployment, (ii) vertical erection, (iii) reconfiguration

4. STRUCTURAL ANALYSIS

4.1 Analysis Model

The numerical investigation of the system was conducted through a progressive form-finding and load-deformation FEA with the software program SOFiSTiK®. The materials and cross-sections were defined through AQUA, while the geometrical definition of the system was produced through the McNeel Rhinoceros program. The SOFiLOAD module was used for the definition of load and ASE as the general static analysis solver. SOFiLOAD and ASE were handled through the alternative text input tool provided by SOFiSTiK, TEDDY. The structure's bending was simulated by taking into consideration both, the external forces and internal material stresses. The system simulations are based on the nonlinear third-order theory, considering geometrical nonlinearities and large displacements. A linear stress-strain behavior of the material of the elastic members has been assumed in the analysis, in order to focus on the geometrical aspects of the active formation process of the system. The analysis follows an incremental induction of bending deformation, where inner stresses of the material developed in each step are stored in the model. The elastic members were modelled as structural surfaces, while all other members as beam elements. The elastic members' section has a height of 200 mm and a thickness of 6 mm. The cables have a diameter of 10 mm and are assigned to prestressing steel Y1770 of 195 GPa elastic modulus and 1520 MPa yield strength. The struts consist of steel hollow sections of 60 mm diameter and wall thickness of 5 mm, whereas their height varies from 70 to 160 cm, successively increasing from the first segment up to midspan.

4.2 System Performance

The overall static height of the erected structure reaches 3.42 m at midspan, and the respective height at the structure's sides, at strip mid-length between the second and third strut, 2.36 m. The reconfiguration of the structure causes a reverse deformation at midspan, reducing thus the height to 1.32 m, Fig. 3. The activation of the cables on the lower row, between the second and third strut, causes the structure's sides to move upwards. The target reconfiguration may be terminated at any step corresponding to a lower maximum stress of 90 % of the respective material's yield strength, depending on architectural, aesthetical, functional etc. criteria.

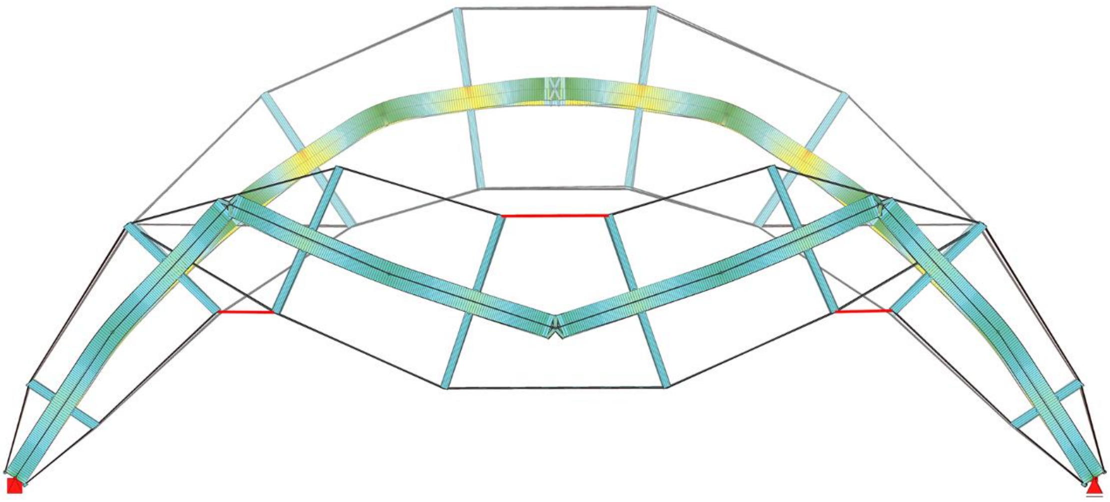

Fig. 3 System deformation behavior at the vertical erection and reconfiguration stage with activation cable segments in stage (iii) indicated with red colour

4.3 Numerical Analysis Results

The analysis results refer to the three above mentioned analysis stages, Fig. 4. The gridshell reaches its target erected configuration with a continuous cables' shrinkage of 301.50 cm, corresponding to a maximum axial force of 0.78 kN. In the subsequent reconfiguration stage a total cable's shrinkage of 88.9 cm has been applied to the lower cables at the system's sides, whereas a cable's shrinkage of 68.3 cm has been applied to the central cable of the upper row. The maximum cable's axial force corresponds to 2.1 kN.

The maximum axial force N_{xx} gradually increases from the planar deployment to the reconfiguration stage, reaching maximum values of 86.18, 99.12 and 138.83 kN/m in each strage, i.e. planar deployment, vertical erection and reconfiguration, respectively. The maximum axial force N_{yy} increases remarkably from the planar deployment to the vertical erection stage, recording values of 7.46 and 39.04 kN/m respectively, whereas at the subsequent reconfiguration stage, it presents a slight increase, reaching the value of 45.25 kN/m. The maximum shear forces V_{xx} exhibit an increase of 56.06 and 232.4 %, from the planar deployment to the vertical erection and the gridshell's reconfiguration, reaching values of 10.72, 16.73 and 35.63 kN/m respectively. The maximum shear forces V_{yy} exhibit an increase from the planar deployment to the erection stage, recording values of 8.51 and 18.80 kN/m, whereas at the following stage, the maximum shear force presents a decrease, recording the value of 15.21 kN/m. Similar to the shear force V_{yy}, the maximum bending moments M_{xx} present an increase of 176. 7 % from the planar deployment to the vertical erection stage, whereas in the subsequent stage the maximum bending moment presents a decrease of 47.06 % when compared to the respective value of the vertical erection stage. The maximum bending moments M_{yy} increase slightly from the planar deployment to the vertical erection stage, whereas at the reconfiguration stage they record identical values with those of the erection stage. In the planar deployment stage, the maximum stresses of the elastic members reach 395.5 MPa, corresponding to a 79.1 % utilisation of their respective material yield strength. Upon completion of the vertical erection stage, the maximum stresses reach a 90 % of the material's yield strength, whereas a notable decrease is registered when the joints are released. The reconfiguration of the system is completed once the maximum stresses reach again 90 % of the material's yield strength, with the maximum value been developed at the elastic strips' zones of the second side struts in span direction.

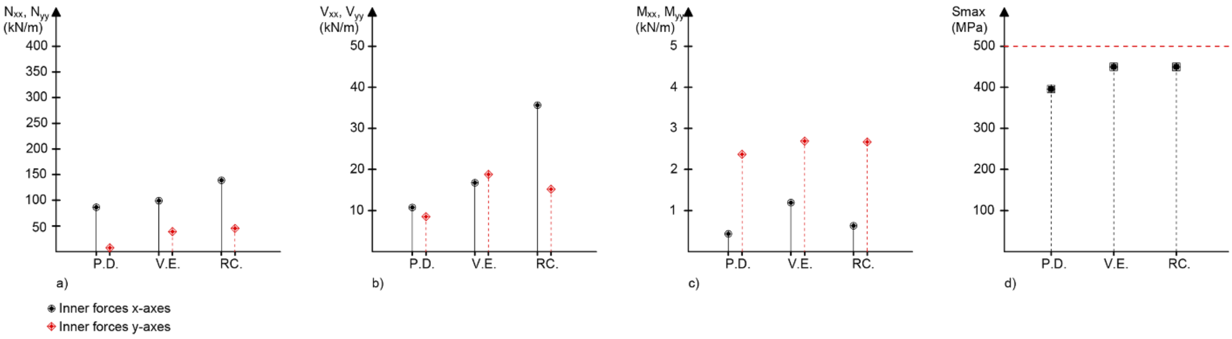

Fig. 4 Numerical analysis results in planar deployment (PD), vertical erection (VE) and reconfiguration stage (RC) of the elastic members; Maximum a) axial force, b) shear force, c) bending moment, d) stress

5. CONCLUSIONS

The present paper investigates the reconfiguration potentials of a hybrid bending-active gridshell. The gridshell consists of four segments of interconnected elastic strips in span direction, placed with their strong axis aligned perpendicularly to the ground and interconnected through controlled joints and a secondary system of struts and cable segments with variable length. The static analysis follows a three-stage development, including the planar deployment of the elastic strips, the vertical erection of the system and its reconfiguration. The gridshell's reconfiguration is handled by releasing the gridshell's internal joints and activating respective cable segments. The cable elements provide the erection of the system, and they serve as actuation components for its reconfiguration. The analysis results suggest that there is a strong interdependency between the cable's shrinkage value and the deformation behavior of the elastic members. The proposed gridshell highlights the structural and architectural potential of hybrid bending-active systems in achieving lightweight, reconfigurable structures. The current investigation demonstrates the efficiency of the proposed gridshell in terms of geometrical transformability. Further work includes experimental investigations with a physical model of the gridshell in providing a proof-of-concept for the proposed activation approach.

REFERENCES

Anastasiadou, I. and Phocas, M.C. (2020), “Deformation control and shape adaptation of a hybrid bending- active gridshell”, Choi, C.-K., (ed.), *The 2020 Structures Congress, Structures20, 2020 International Conference on Advances in Computational Design*, Seoul, Korea.

Douthe, C. and Stefanou, I. (2021), “In-situ experiment on long-term behaviour of GFRP pipes under permanent bending.” *Construction and Building Materials*, **284**, 1-12.

Gengnagel, C., Lafuente Hernández, E. and Baumer, R. (2013), “Natural-fibre-reinforced plastics in actively bent structures.” *Construction Materials*, **166**, 365-377.

Kotelnikova-Weiler, N., Douthe, C., Lafuente Hernández, E., Baverel, O., Gengnagel, C. and Caron, J-F. (2013), “Materials for actively-bent structures.” *International Journal of Space Structures,* **28**, 229-240.

La Magna, R. (2017), *Bending-active plates – Strategies for the induction of curvature through the means of elastic bending of plate- based structures*, Doctoral Thesis, University of Stuttgart.

Lafuente Hernández, E. (2015), *Design and optimisation of elastic gridshells*, Doctoral Thesis, Berlin University of the Arts.

Liddell, I. (2015), “Frei Otto and the development of gridshells.” *Case Studies in Structural Engineering*, **4**, 39-49.

Lafuente Hernández, E., Gengnagel, C., Sechelmann, S. and Rörig, T. (2012), “On the materiality and structural behaviour of highly-elastic gridshell structures”, *Computational Design Modelling*, Heidelberg, Berlin, Germany, 123-135.

Lienhard, J. (2014), *Bending-Active Structures – Form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein, Doctoral Thesis*, University of Stuttgart.

Lienhard, J. and Gengnagel, C. (2018), “Recent developments in bending-active structures”, *Proceedings of the IASS Annual Symposium 2018, Creativity in Structural Design*, MIT, Boston, USA, 1-8.

Phocas, M.C. and Alexandrou, K. (2018), “Numerical analysis and cable activation in hybrid bending-active structures with multiple cables.” *Engineering Structures*, **174**, 561-572.

Phocas, M.C., Alexandrou, K. and Athini, S. (2019), “Design and analysis of an adaptive hybrid structure of linearly interconnected scissor-like and cable bending-active components.” *Engineering Structures*, **192**, 156-165.

Phocas, M.C., Christoforou E.G. and Matheou, M. (2015), “Design, motion planning and control of a reconfigurable hybrid structure.” *Engineering Structures*, **101**(10), 376-385.