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Design and analysis of form-active systems. Spanning from tensile to hybrid bending-active structures

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Abstract

The paper investigates design and analysis aspects of lightweight form-active systems. In particular, the realization of the roof structure of Munich 1972 Olympics-Arenas and the initiation of numerical methods of analysis form the frame of the current presentation in three phases of development: design and computational analysis, design optimization and automated manufacture, and form-active systems' performance-based design. Following a brief review of the initial two phases of development, a number of prototype case examples of hybrid bending-active structures exemplify the simulation and analysis processes followed in the integral design of form-active systems with inherent adaptive characteristics.

Keywords

Adaptive structures, Tensile, Membrane, Cable bending-active structures, Finite-element analysis, Nonlinear analysis.

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Introduction

Lightweight tensile structures stand out as an exemplary field that revolutionized architectural technology and engineering in the early 70´s, establishing, at the same time, new frame conditions and methodologies with regard to the interdisciplinary design and numerical analysis conducted (Otto, 1967). In contemporary architecture, cable-net, membrane and bending-active structures are considered as form-active systems (Engel, 1999), expressing visually any acting load or pressure on the structural members' own shape distortion (Lienhard and Knippers, 2013). Depending on the boundary conditions and the individual structural members' stiffness, a variety of equilibrium forms are developed. Thus, the form, the material and stress distribution for these structures are conditioned reciprocally.

The development and realization of the lightweight structure of the Munich Olympics-Arenas historically represents the first architectural-engineering design approach of long-span cable-net structures. At the same time, the project in question led to the first large-scale computer applications. The finite-element method was, for the first time, expanded and applied internationally for the design, development and analysis of this particular structure.

Succeeding advances in digital design technology enabled linear design developments ranging from the conceptual design to the analysis, production and fabrication. Early phases of digital technology integration provided possibilities for a shift from mass-production to mass-customization, relating, at the same time, the principles of the former to the advantages of individual fabrication. Related processes were based on the coupling of computer-aided design, structural design, manufacturing and rapid prototyping. At the same time, performance based architecture was shaped based on more or less interactive, iterative closed loop design processes with regard to the original form conception, optimization and realization (Mistur, 2007).

From a bottom-up design approach the characteristics of related integral form-generation processes may be examined according to their performative capacity, as interrelated from early phases to the material constituents (Hensel, Menges and Weinstock, 2010). Due to the fact that lightweight form-active structures do not possess any timely invariant defining state, while their deformability is primarily influenced by the respective geometrical characteristics and stresses of the members, the design and analysis takes into consideration the entire transformation process, from the planar to the form-found state. In this frame, both the erection process and the load-deformation behavior of the systems are of significance throughout the interactive design and analysis process. Such step-by-step simulation processes are briefly presented with three case examples of hybrid bending-active structures. By extent, the systems may acquire multiple equilibrium states according to respective possible functional and performative requirements.

The Olympic Stadium of Munich

When the first prize of the architectural competition for the sporting premises of the 20th Olympic Games in 1972 in Munich was awarded to the Stuttgart architects Behnisch and Partners with Juergen Joedicke in 1967, the advantages of the design were obvious, arising from the main architectural idea for a transparent, unusual and innovative tent roof (Figure 1). The competition results were documented in the German architectural press as follows: "…The built form is not the primary, but the aim conception for a task, which exactly is not derived from a formal aspect, but from the nature

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of the problem. And for this, the technological construction possibilities ought to be found" (Wallenborn, 1967).

Five months later, Behnisch and Partners were commissioned with the construction of the sport premises on the southern area of the Olympic park. The prestressed cable-net roof was set to further planning. Soon after, a timber and a perlite concrete covering of the net were abandoned, as well as a timber gridshell solution; all systems were too stiff for the selected roof shape. Frei Otto and his team then found a preliminary tensile solution through model studies. In lack of other solutions, tulle models were initially measured photogrammetrically to ascertain the required cutting pattern. At the time, only model techniques, geometrical expedients and idealized calculation methods were used and were adequate for relatively simple forms. To that end, construction possibilities would compensate for the insufficiencies of the design, the construction planning and the erection on site. Such a simplified design method had already been practiced by Frei Otto with Rolf Gutbrod and Fritz Leonhardt for the preceded German pavilion of the Expo 1967 in Montréal. Even in the design of elastic gridshells, form-finding of the structures was investigated, at the time, by merely using empirical calculations, physical modelling in smaller and actual scale, or even the designer's intuition (Quinn and Gengnagel, 2014). The Mannheim multihall, designed by Frei Otto in 1973, is an indicative example of the structure's morphological capabilities achieved through implementation of bending-active members. The final shape of the structure was estimated only by using the hanging chain model technique (Liddell, 2015). Nevertheless, in the case of the lightweight structure in Munich, precision was required, among others, to determine the cables' length under the planned prestress, material related issues, such as cable anchorages and fittings, as well as prefabrication.

Analytical Form-finding

The most influential aspect in the realization of the lightweight structure in Munich was the development and application, for the first time, of the finite-element analysis method by John H. Argyris[1]. Computer oriented calculation methods, that were developed at the Institute of Statics and Dynamics for Aerospace Structures at the University of Stuttgart, and by that time successfully applied, offered the decisive momentum. The most important contribution of Argyris' original research on energy theorems and structural analysis had been the matrix methods of analysis applicable to structures composed of discrete elements and therefore, ideally suited for modern automatic computation[2]. This respectable background formed a major contribution to the creation of the revolutionary finite-element analysis method.

1. Following Civil Engineering studies at the Technical Universities of Athens and Munich and post-graduate studies in Aeronautics and Mathematics at the Technical Universities of Berlin and Zurich, John H. Argyris became director of the Research Department of the Royal Aeronautical Society, from 1943 to 1949, and joined the University of London, Imperial College of Science and Technology, as Senior Lecturer in 1949, Reader in the Theory of Aeronautical Structures from 1950 to 1955, and Professor of Aeronautical Structures between 1955 and 1975. He was appointed Professor at the University of Stuttgart in 1959, Director of the Institute of Statics and Dynamics of Aerospace Structures between 1959 and 1984, and subsequently Director of the Institute of Computer Applications from 1984 to 1994, which became one of the most renowned of its kind in the world.

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Computational analysis of lightweight structures encompasses each individual element with a unified calculation process. However, a direct application to the stated problem formulation for such structures was initially not possible. New developments regarding theory and calculation programs with appropriate formulation and design of the second and fourth analysis step became necessary and had to be worked out in very limited time (Figure 2). The static equilibrium of the prestressed net was investigated through iterative geometrical nonlinear elastostatic analyses. The investigated form of the structure was, at first, approximated and then numerically improved, until equilibrium at the required prestress level was achieved. In general, the origin can even be a flat net that is prestressed between fixed points in plane. For every displacement state of the supports, the related equilibrium form of the prestressed net is iteratively investigated. The procedure can also be described as the numerical simulation for a stepwise hanging of the net from the origin plane (Figure 3).

An in-depth study for the evaluation of the gained experience, in terms of integration and consolidation of the disciplines involved, succeeded the project realization. The suspended cable roof of the Olympic Stadium of Munich initiated a period dedicated to automatic form generation. The conclusion of the research on the form-finding, the statics and dynamics of long-span net structures, formed the basis for the subsequent development of modern software programs for nonlinear structural analysis. The developed calculation procedures were expanded and applied in subsequent studies, such as the Stadium of Niedersachsen in Hanover and the Olympic Stadium of Montréal.

Towards Interdisciplinary Iterative Design Processes

Apart from the origin and application of computational analysis in design, the example of the Olympic Stadium of Munich also demonstrates aspects of prefabrication, standardization and consequent industrial production and erection that had been actively pursued by the design team. The use of as many equal components as possible, arranged and joined in the simplest possible way, was paradigmatic. A further example to this general concern, in terms of construction and materialization, is Buckminster Fuller, who had worked intensively for over 50 years on the geometrical laws of geodesic domes (Hays and Miller, 2008). Topologies for spherical shell structures were developed that allowed the use of as many identical beam and node elements as possible (Krausse and Lichtenstein, 2000). Same holds for Konrad Wachsmann (Wachsmann, 1989). Furthermore, the professional success of Max Mengeringhausen, the founder of Mero, was due to an intelligent solution for a nodal connector for space structures (Kurrer, 2004).

2. The comprehensive analytical research work performed by Argyris at the Royal Aeronautical Society on elements of the elastic aircraft was included as part of the Handbook of Aeronautics No. 1 in the early 50's, Argyris, J. and Dunne, P.C., 1952. *Structural Analysis, Structural Principles and Data, Part 2, Handbook of Aeronautics, 1*. London: The New Eva Publ. Co. Ltd. The work on energy theorems and structural analysis undertaken at Imperial College, originally published in a series of articles in Aircraft Engineering between October 1954 and May 1955, was published as a book in 1960, followed by four further editions until 1977, Argyris, J. and Kelsey, S., 1960. *Energy Theorems and Structural Analysis*. London: Butterworths.

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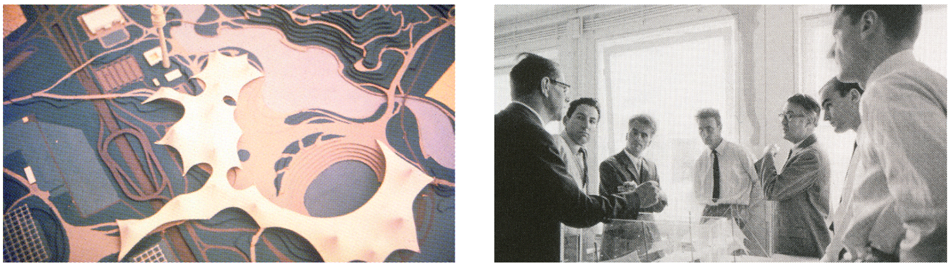

Figure 1.
Tulle model of architectural competition entry for the Olympic Stadium of Munich 1972 and discussion round on the realization of the project among Heinz Isler, Fritz Auer, Frei Otto, Jörg Schlaich, Rudolf Bergermann and Knut Gabriel (l. to r.), (Bögle, *et al.*, 2003)

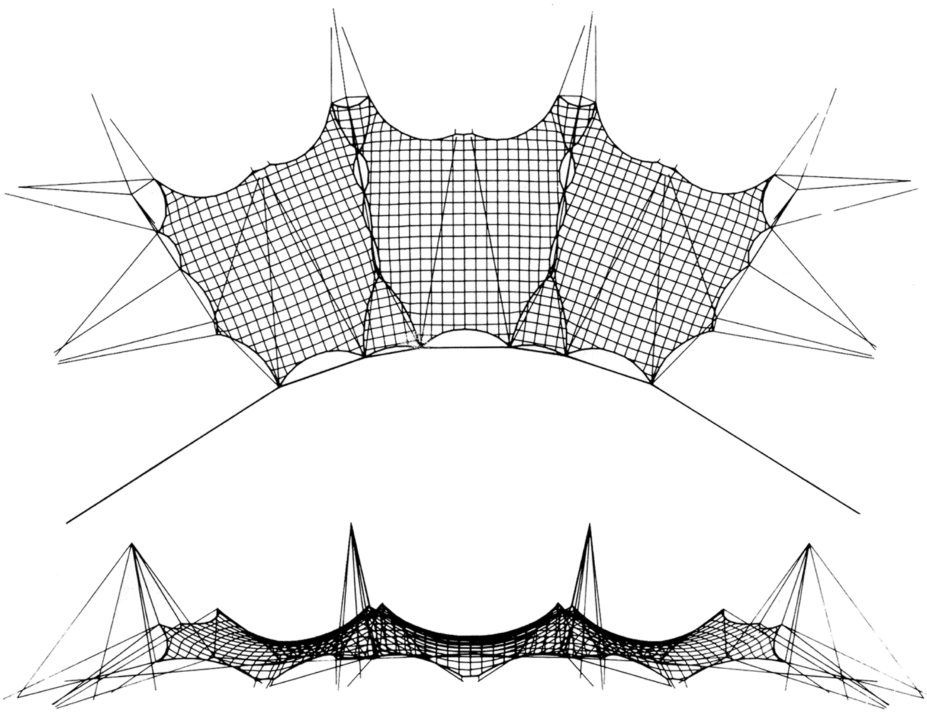

Figure 2.
Analytical form-finding of the east tribune with finite-elements (Doltsinis, 1990)

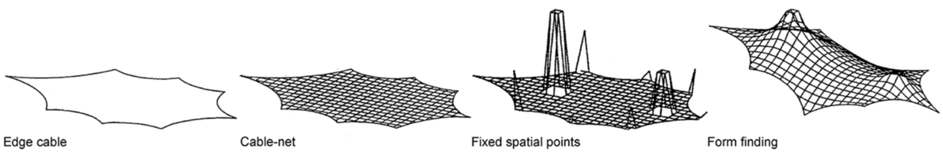

Figure 3.
Principle procedure for analytical form-finding of lightweight structures

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Since the early 90's, such considerations have been of minor relevance to modern computer-aided manufacturing techniques; this applies for example to the milling geometry of any joint and the implicated production process (Knippers and Speck, 2012). In recent years, numerous cable-net shells have been constructed of steel rods and glass plates, taking over an important model role in the steel construction industry in terms of developing digital design and production chains. Initially, smooth free-form surfaces of the overall shape, generated through a three-dimensional modeling program, are transformed into a viable structural system. In most cases, the shape is modified to act like a shell structure, while the geometrical optimization provides a smooth curvature. As a second step, the three-dimensional geometry is transformed into a structural grid, i.e. triangular net that forms the gridshell. An automatic transformation into a triangular net provides faceted edges, irregularity of the meshes and different node connections. This step involves the grouping and smoothing of the grid characteristics. The final step consists of the structural analysis of the net. The data file that is used for the dimensioning of the members is also used for delimiting all the parameters of the geometry for fabrication purposes. Relevant examples include, among others, the stainless-steel roof over the courtyard for the Deutsche Bank in Berlin, Pariser Platz 3 by Gehry Partners and Schlaich, Bergermann and Partners, and the roof for the courtyard of the British museum in London, by Foster and Partners and Buro Happold. In this context, the lightweight roof structure at the central entrance area of the Expo 2010 in Shanghai, designed almost 40 years after the precedent Olympic Stadium of Munich, by the architectural office SBA, Stuttgart/Shanghai, in collaboration with Knippers Helbig Advanced Engineering, Stuttgart/New York, is undoubtedly exemplary for its comprehensive design that was primarily directed by functional and extreme environmental conditions at the site, as well as by structural constraints of the geometrically refined overall design form and automated fabrication processes (Figure 4). The project reveals broader characteristics of discrete nonlinear iterative performance-based design developments with regard to the original form conception, optimization and realization.

Integral Design and Analysis Processes

The role of digital design and computational analysis in the conceptualization and development of lightweight structures up to date is indicative of a new syntax of emerging design. Further research in all operation stages, including the form-finding and erection stage, as well as the loading stage of the structure, is feasible through a bottom-up approach, in order to achieve efficiency, sustainability and technological innovation (Gibson, 2012).

Along these lines, a number of case examples are briefly presented in the following sections of the paper. A case example of a gridshell structure, composed of bending-active strips in pairs, demonstrates the advantages of form-active systems in the erection and load-deformation behavior. The coupling of bending-active members with a secondary system of cables and struts may provide longer spans and variable system configurations. Finally, the interconnection of bending-active members with kinetic components, such as scissor-like elements, enables further controlled structural adaptiveness.

The common feature, in all case examples presented herein, is the utilization of structural materials with high elastic modulus and yield strength that provide mechanisms with adaptive physical behavior. Compared to technical linkage systems, bending-active mechanisms replace local hinges by elastic deformations of their members and thus distribute the acting forces over a wider area in which bending takes place (Lienhard, 2014). Following the pioneering work of Frei Otto, Edmund Happold and Rolf Gutbrod (Happold and Liddell, 1975; Quinn and Gengnagel, 2014; Liddell, 2015), the appli-

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Figure 4.
Aerial view of the lightweight tensile roof structure of the Expo 2010 in Shanghai (Knippers, 2011)

cation of bending-active plate members has recently been demonstrated with a pavilion prototype construction with birch plywood lamellas at the University of Stuttgart in 2010 (Fleischmann, *et al.*, 2012) as well as with a Biomimetic Media Façade with flexible shading elements at the Thematic Pavilion at Expo 2012 in Yeosu, South Korea (Knippers, *et al.*, 2012). In principle, the simulation of any form-finding process using finite-element analysis requires that the actuated for erection and force-driven deformation of the structure are considered in the same modelling environment, following a step-by-step nonlinear approach (Phocas and Alexandrou, 2017). This ensures that residual stresses of the structural members can be identified and stored in all stages of the analysis when investigating the exact behavior of the system in terms of increasing geometrical stiffness.

Bending-active Plate Gridshell

The bending-active plate gridshell consists of primary elastic strips placed on their strong axis and interconnected through steel rings and telescopic bars (Phocas, Alexandrou, Zakou, 2016). In span direction, the supports are interconnected through cables with variable length (Figure 5). The supports enable free displacements on the x and y-axis, until the system has reached its form-found shape. A single corner support is fixed to the ground, in order for the system to maintain a stable reference point. Once the structure is stabilized, peripheral telescopic bars are applied for further deformation control. Thus, the system, in its form-finding process, incorporates a) control deformation mechanisms through the elastic properties of the primary members, modeled as beam elements and assigned to elastic material properties PTFE (Polytetrafluorethylene) of high elastic mod-

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ulus, b) the length modification of the cables connecting the supports and c) the elastic members' coupling telescopic bars. The bending-active strips have non-deformed length of 7.5 m and a span of 5.1 m in the fixed position of the system.

Finite-element analysis of the system is based on the third order theory. Given that the material behaves linear elastically in the case in question, the analysis considers geometrical nonlinearities, as well as large system deformations. Sequential, step-by-step structural modifications are followed, in order to gradually investigate the structure's deformations in obtaining the final form-found position. In each consecutive analysis step, the residual stresses, stored by the members and the updated geometry of the system, are taken into consideration. The static analysis of the bending-active gridshell throughout the deformation process is divided into three main stages with a number of sub-stages in-between, as shown in Figure 6. The first stage refers to the 'planar deformation' and considers the expansion of the units by gradually increasing the internal bars' length at a certain initial value. The 'erection approach' follows in stage 2. At this stage, the reduction of the lower cables' length, connecting the supports in span direction, causes upwards deformation of the system. When the structure has attained its maximum height, all supports are set to 'fixed'. In the final 'morphology optimization process' of stage 3, further modification of the telescopic bars' length is induced, in order to examine their influence on the system's deformation behavior preceding the concluding loading stage. At first place, the bending-active plate gridshell demonstrates the advantages of deployability, self-erection, geometrical transformability and self-stabilization.

Hybrid Cable Bending-Active Structure

A hybrid cable bending-active structure has been proposed as a way to achieve longer structural spans (Kontovourkis, *et al.*, 2017). The design is based on a primary unit component. On the horizontal plane, the unit consists of a pair of vertically oriented PTFE lamellas, interconnected at mid-length, and deformed in inverse direction, to form a curvilinear symmetric shape. Cable and strut elements stabilize the primary elastic members by connecting them at both ends in longitudinal and transverse direction respectively (Figure 7). The overall structure is composed of six, consecutively connected units, assembled in linear arrangement. Prior to applying the secondary members, horizontal struts are added in-between each consecutive unit for stability purposes.

The structure acquires three arc-like configurations, controlled by the secondary system of cables with variable length and with struts positioned at the periphery of the primary system's span. In principle, the position of the struts, as to the primary members, plays a critical role in the overall shape of the structure. In this respect, three configurations are defined, resulting in distinctive arc-like configurations, whereas the secondary cables are only activated in tension. An arc-like shape in elevation is obtained by positioning all strut elements facing the inner side of the structure. In another configuration alternative, a stronger primary system's curvature develops near the supports, while struts are only placed at nodes 1, 3 and 5. At nodes 1 and 5, struts are placed at the inner side of the system, while at node 3, at the exterior side. In another configuration alternative, the struts in nodes 1, 3 and 5 are oriented in opposite directions.

The form-finding of the systems is divided into two stages. At the first stage, the linearly arranged units, with total length of 16 m, are deformed using cable shrinkage values of 300 mm. Consequently, the span of the primary system shrinks from 16 to 15 m. In the subsequent stage of analysis, all members of the structural assembly are considered. Shrinkage values, varying from 300 to 500 mm,

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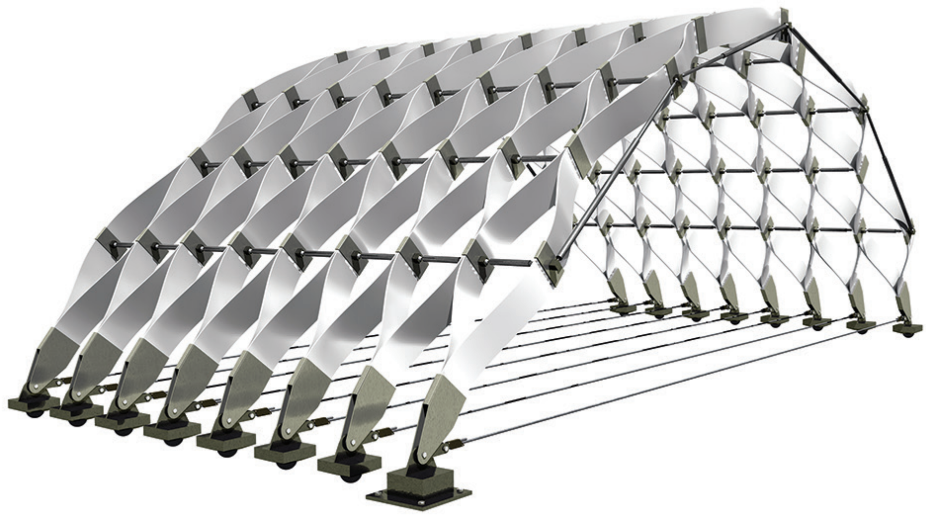

Figure 5.
Bending-active plate gridshell

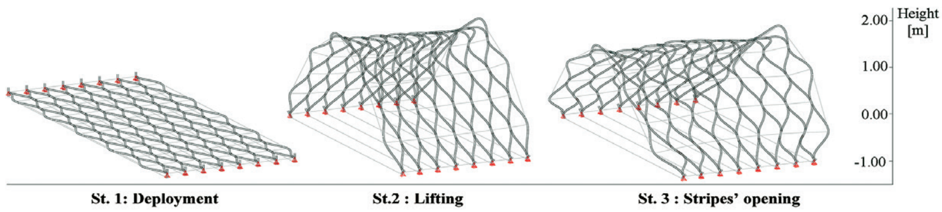

Figure 6.
System transformation stages

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are introduced for all cables of the secondary system. Due to the eccentricity of the applied force, the primary structure is forced to deform in vertical direction through torsional deformation of the elastic members. The cable shrinkage values vary respectively, in order to achieve a deformed system span of 12.5 m in all configurations (Figure 8).

The finite-element analysis conducted verified, at first place, the interactive load transfer between the primary and secondary cables from one configuration to another and the ability of the primary structure to adapt into variable shapes through the secondary system. Furthermore, all examined system configurations exhibited only minimum deformations under external vertical loading. Compared to conventional catenary structures, the proposed hybrid cable bending-active prototype offers higher flexibility in its configurability. At the same time, gradual cable length modifications of the secondary cables provide target shapes of the system, by avoiding complex and unsafe erection stages.

Adaptive Beam of Scissor-like and Cable Bending-active Elements

The adaptive beam consists of scissor-like elements (SLEs) assembled in series with pairs of inversely curvilinear bending-active members (Phocas, Alexandrou, Athini, 2017), consisting of PTFE material and positioned on the weak axis (Figure 9). The development of the system follows a two-stage process that consists of the form-finding and loading stage. At the first stage, the SLEs are linked together in series with the bending-active members placed in pairs. Form-finding of the system is based on a step-by-step length decrease of the cable interconnecting the supports, which comprises the primary actuation means of the system. Starting off with a non-deformed length of 12 m, the system's resulting span amounts to 6 m. Throughout the form-finding process, the SLEs decrease their relative angles, while the bending-active members in each pair are curved inversely. Subsequently, the supports are transformed into fixed ones, the elements are fastened together by contracting cables and the beam obtains a respective curvilinear configuration. Once the system is form-found, the central joints of the SLEs are locked via electromagnetic brakes, while cables are added to the bending-active members (Figure 10). The process is governed by two parameters: a) the material strength limits throughout the form-finding process and b) the stiffness of the bending-active members under loading. The maximal members' curvature corresponds to exclusively elastic stresses of the members, avoiding permanent deformations or failure. At the same time, the prestress of the members needs to be sufficiently high to reach adequate geometric stiffness with regard to their deformations under loading. Consequently, implementation of the bending-active members in pairs, and their subsequent coupling with cables, aims at increasing the stiffness of the elements and improving the load-deformation behavior of the system.

The proposed structure composition aims at expanding the system's transformation capability, adaptiveness and form flexibility, while building on the advantageous behavior of its components, i.e. SLEs for deployability and stability, bending-active members for lightweight, configurability, adaptiveness and reversible elasticity, and coupling cables for deformation limitation under loading. Implementation of the bending-active members also decreases the technical complexity and packaging volume of the system before erection. The curvature of the system varies according to the position of the SLE joints, the geometry and the degree of bending of the elastic members, resolving the transformations on an intrinsic, element-level and thus relieving the nodes.

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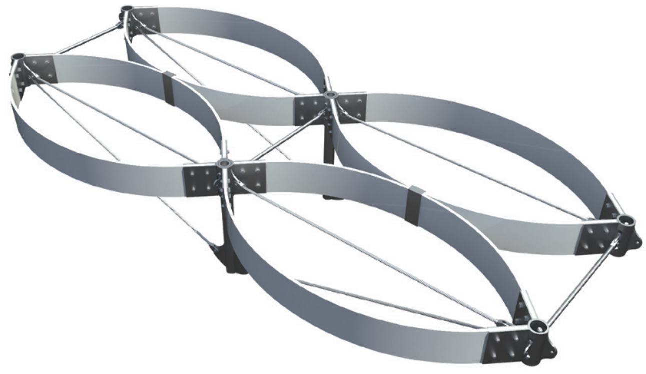

Figure 7.
Typical units assembly of hybrid cable bending-active structure

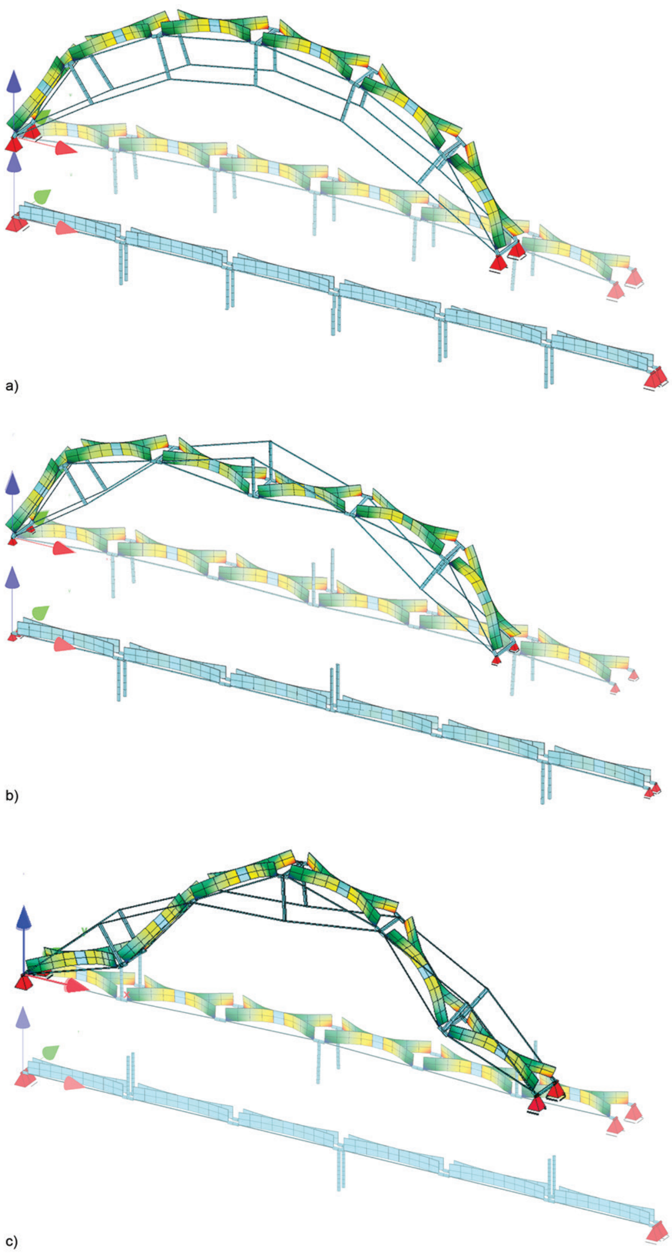

Figure 8.
Systems' transformations: Non-deformed shape, linear primary members' deformation and arc-like system configuration

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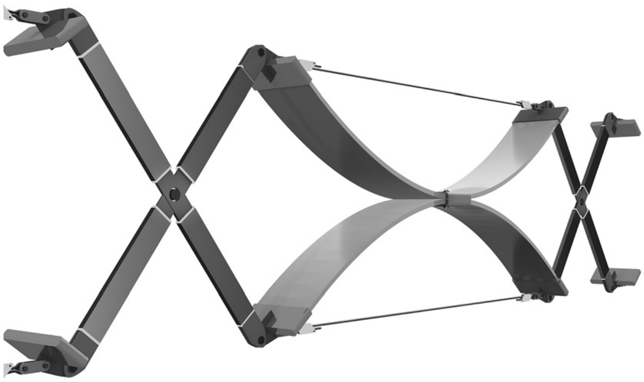

Figure 9.
Scissor-like and cable bending-active members' assembly

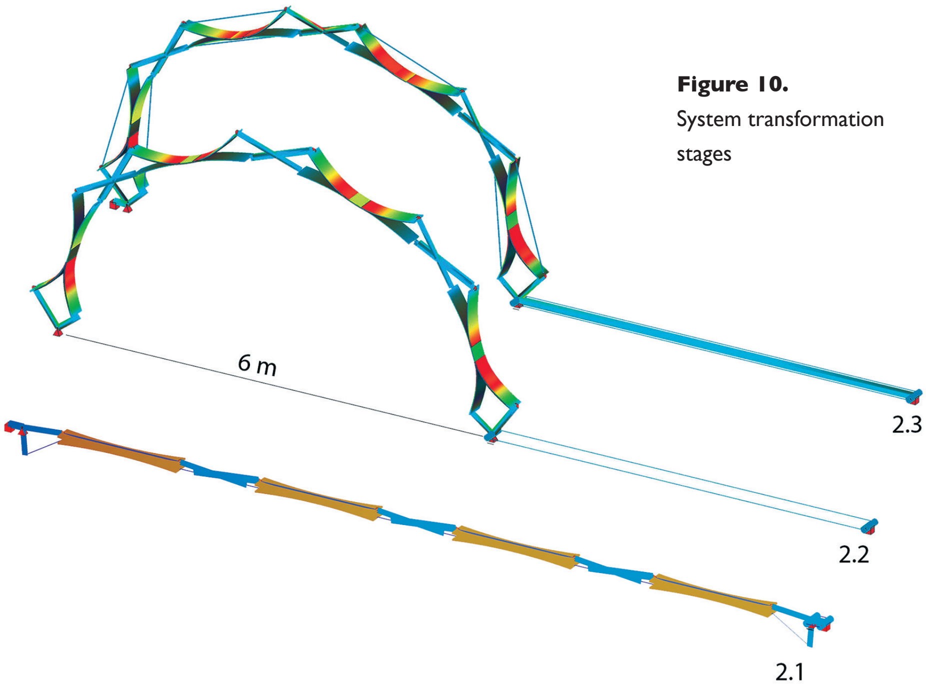

Figure 10.
System transformation stages

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Conclusions

The brief review of the design and realization of long-span lightweight tensile structures, with reference to the example of the tensile cable-net structure of the Olympic Stadium of Munich that had been enabled through the development and application of the finite-element analysis, is representative of a subsequent initiation of automatic form generation. The conclusions of the research on the form-finding, the statics and dynamics of long-span net structures formed the basis for the subsequent development of modern program systems for nonlinear structural analysis. Almost 40 years later, the membrane structure of the Expo 2010 in Shanghai demonstrates that the methodology of design and analysis of such structures follows similar modes, primarily aiming at a structural form refinement and automated fabrication. Enabled through contemporary advancements in computational design and numerical analysis, the form-finding procedure in form-active systems may comply with the coherent development of material, form and structure and further project the role of architecture and engineering within the design process. In demonstrating this, three prototypes of hybrid bending-active structures are here presented with regard to their design and analysis conducted. In achieving lightweight, form flexibility and adaptiveness, the analysis considers all system transformation stages. By extent, form-active systems may result from open-loop development processes and obtain variable characteristics following interactive tuning of their form and load-deformation behavior.

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References

Bögle, A., Schmal, P.C. and Flagge, I., eds, 2000. *Leicht Weit – Light Structures. Jörg Schlaich Rudolf Bergermann. Olympic roof Munich (1972)*. Munich: Prestel, pp. 96-103.

Doltsinis, I., 1990. Computermethoden der Tragwerksberechnung. In: G. Brink mann, ed. *Leicht und Weit. Zur Konstruktion weitgespannter Flächentragwerke*. Weinheim: VCH Verlagsgesellschaft mbH, pp. 170-189.

Engel, H., 1999. *Structure Systems*. Ostfildern-Ruit: Gerd Hatje Verlag, 2nd edn.

Fleischmann, M., Knippers, J., Lienhard, J., Menges, A. and Schleicher, S., 2012. Material Behavior. *Architectural Design*, 216, pp. 44–51.

Gibson, M.D., 2012. Technology Overlap and Synthesis in the Architectural and Engineering Disciplines. *Architectural Engineering Technology*, 1. Online: http://www.dx.doi.org/10.4172/jaet.1000e102.

Happold, E. and Liddell, W.I., 1975. Timber Lattice Roof for the Mannheim Bundesgartenschau. *The Structural Engineer*, 53, 3, pp. 99-135.

Hays, K.M. and Miller, D., 2008. *Buckminster Fuller – Starting with the Universe*. New York: Whitney Museum of American Art and Yale University Press.

Hensel, M., Menges A. and Weinstock, M., 2010. *Emergent Technologies and Design: Towards a biological Paradigm for Architecture*. Oxford: Roudledge.

Krausse, J. and Lichtenstein, C., 2000. *Your Private Sky. R. Buckminster Fuller Design als Kunst einer Wissenschaft*. Zurich: Lars Mueller.

Knippers, J., 2011. Megastructure – Expo Shanghai 2010. Knippers Helbig Avanced Engineering. In: S. Stratis, M.C. Phocas, P. Pyla, C. Hadjichristos and N. Charalambous, eds. *Journal of Architecture, J.UCY-02*. Nicosia: Department of Architecture, University of Cyprus.

Knippers, J., Jungjohann, H., Scheible, F. and Oppe, M., 2012. Bio-inspired Kinetic GFRP-façade for the Thematic Pavilion of the EXPO 2012 in Yeosu. *International Symposium of Shell and Spatial Structures, IASS 2012*, 90, pp. 341–347.

Knippers, J. and Speck, T., 2012. Design and Construction Principles in Nature and Architecture. *Bioinspiration & Biomimetics*, 7. Online: http://iopscience.iop.org/1748-3190/7/1/015002.

Kontovourkis, O., Phocas, M.C., Alexandrou, K. and Frangogiannopoulos, S., 2017. Configuration and Deformation Control of a Hybrid Bending-Active Structure. Special Issue: Mobile, Adaptable and Rapidly Assembled Structures, *Computational Methods and Experimental Measurements*, 5(4), pp. 475-483.

Kurrer, K.-E., 2004. Max Mengeringhausen. Ein Komponist von Raumfachwerken. *deutsche bauzeitung*, 10, pp. 88-95.

Liddell, I., 2015. Frei Otto and the Development of Grid Shells. *Case Studies in Structural Engineering*, 4, pp. 39–49.

Lienhard, J., 2014. *Bending-Active Structures: Form-Finding Strategies using Elastic*

ISSN 2309-0103
www.enhsa.net/archidoct
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Deformation in Static and Kinematic Systems and the Structural Potentials Therein. Ph.D. Thesis, Research Report 36. Stuttgart: Institute of Building Structures and Structural Design, University of Stuttgart.

Lienhard, J. and Knippers, J., 2013. Considerations on the Scaling of Bending-Active Structures. *Space Structures*, 28, pp. 137–148.

Mistur, M., 2007. Design Research Practices. In: K. Wingert-Playdon and H. Neuckermans, eds. *Emerging Research and Design, EAAE Transactions on Architectural Education*, No. 32, Brussels: EAAE, pp. 37–47.

Otto, F., 1967. *Tensile structures: Design, Structure and Calculation of Buildings of Cables, Nets and Membranes.* Cambridge: MIT Press.

Phocas, M.C. and Alexandrou, K., 2017. Adaptive Structures. Soft Mechanical Approach. Special Issue: Mobile, Adaptable and Rapidly Assembled Structures, *Computational Methods and Experimental Measurements*, 5(4), pp. 421-431.

Phocas, M.C., Alexandrou, K. and Athini, S., 2017. *Design of an Adaptive Hybrid Structure.* Nicosia: Department of Architecture, University of Cyprus.

Phocas, M.C., Alexandrou, K. and Zakou, C., *Design and Analysis of an Adaptive Bending-Active Plate Gridshell.* Nicosia: Department of Architecture, University of Cyprus.

Quinn, G. and Gengnagel, C., 2014. A Review of Elastic Grid Shells, Their Erection Methods and the Potential Use of Pneumatic Formwork. In: *Mobile and Rapidly Assembled Structures IV.* Ostend: WIT Press, pp. 129–144.

Wachsmann, K., 1989. *Wendepunkt im Bauen*. Stuttgart: Deutsche Verlags-Anstalt DVA.

Wallenborn, J.K., 1967. Für die XX. Olympischen Spiele 1972 in München…, Ergebnisse des Städtebau- und Bauwettbewerbs. *deutsche bauzeitung*, 11.