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Transformability in adaptive structures of Frei Otto and beyond

Transformabilidad en las estructuras adaptativas de Frei Otto y más allá

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Abstract: Adaptive structures can conform to external changing conditions, in order to improve their functional, energy related and/or load-bearing behavior. Structural adaptation can be depicted in the work of Frei Otto on lightweight tensile structures and elastic gridshells of reduced structural mass and materials with high strength and relatively low elastic modulus respectively. The main developments achieved were based on transformability in the structural simulation and erection process. Representative examples include the Olympic Stadium in Munich in 1972 and the Mannheim Multihalle in 1975 respectively. With the rise of digital and numerical technology in the last 20 years, Frei Otto's ideas and concepts are even more important and relevant today than they were half a century ago when they first emerged. Meanwhile, research and development of actual adaptive structures are based on the afore-mentioned principles of form variation and lightweight, as well as on aspects of flexibility, controllability and simplicity in kinematics. In achieving this, the development of adaptive structures with minimum embedded actuation and maximum possible output structural states, gains significance. Selected prototype developments demonstrate related achievements in the area.

Keywords: transformable structures; adaptive structures; lightweight structures; elastic gridshells; form-finding.

Resumen: Las estructuras adaptativas pueden adaptarse a condiciones externas cambiantes para mejorar su comportamiento funcional, energético y/o de carga. La adaptación estructural puede representarse en los trabajos de Frei Otto sobre estructuras ligeras de tracción y cáscaras de rejilla elásticas de masa estructural reducida y materiales de alta resistencia y módulo elástico relativamente bajo, respectivamente. Los principales avances logrados se basaron en la transformabilidad en el proceso de simulación y montaje estructural. Algunos ejemplos representativos son el Estadio Olímpico de Múnich en 1972 y el Multihalle de Mannheim en 1975, respectivamente. Con el auge de la tecnología digital y numérica en los últimos 20 años, las ideas y conceptos de Frei Otto son aún más importantes y relevantes hoy que hace medio siglo, cuando surgieron por primera vez. Mientras tanto, la investigación y el desarrollo de estructuras adaptativas reales se basan en los principios antes mencionados de variación de forma y ligereza, así como en aspectos de flexibilidad, controlabilidad y simplicidad en la cinemática. Para lograrlo, cobra importancia el desarrollo de estructuras adaptables con un mínimo de actuación incorporada y un máximo de estados estructurales de salida posibles. Una selección de prototipos demuestra los logros alcanzados en este campo.

Palabras clave: estructuras transformables; estructuras adaptativas; estructuras ligeras; rejillas elásticas; búsqueda de formas.

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INTRODUCTION

The development of a sustainable built environment is based on aspects of technological advances enabling productivity, effectiveness, ecological and environmental awareness, reduction of energy consumption and economic costs on one hand, as well as mass-customization and variability on the other. Simultaneously, the negative impact of increased population growth on the environment, realization of static heavyweight structures and global humanitarian crises, brought about the need for easily adaptable and even mobile structures that can be assembled and disassembled. Such structures favor automated erection processes, lightweight construction and innovative materials in achieving structural flexibility and adaptiveness to changing functional requirements, as well as to varying external environmental and/or loading conditions.[1] The technological development of building structures with large identification features to their environment is based on their character of adaptiveness.

In architecture, the development of an adaptive built environment was initially driven by industrialization and mass production, associated with high flexibility in the building's spatial composition and tectonics. In engineering, it was initially favored through reduced structural mass and high strength materials of relatively low elastic modulus. In this framework, Frei Otto's work on the transfer of natural solutions in the design of structures was decisive in several ways.[2] Within this fundamental research, different physical models, such as soap bubbles and spring linkages, were investigated in search of optimized structural shapes with minimum material. Most importantly, Frei Otto's research in the area of long-span lightweight tensile structures and elastic gridshells, was decisive in the development and application of the concept of structural adaptiveness. His research aimed at maximum structural efficiency with minimum means and material.

The concept of adaptiveness in structural systems was showcased in two representative projects; the Olympic Stadium in Munich in 1972 and the Mannheim Multihalle in 1975. These projects utilized form-active systems, which were simulated, analysed for their load-deformation behavior and erected.[3] The design of the Olympic Stadium in Munich was based on an original extension and application of the Finite-Element Method for the numerical simulation of the form-finding process of the structure.[4] The design and analysis considered its entire transformation, from the initially planar to the form-found state. During the erection of the Mannheim Multihalle prototype, this transformation was essential to the structural members. Consequently, the design of these systems was based on two principles: the relaxation of a cable-net according to the natural forces acting therein and its stabilization through prestress, as well as the deformation of an initially planar grid of bars into a curved shape and its stiffening.

The structural shape is a result of an interactive process of 'form-finding' that is traced back to the analysis and erection of the structure. In the first case, the final equilibrium form of the cable-net depends on the boundary support conditions, while the individual structural members' stiffness is defined through their mechanical properties and prestress.[5] The structural shape comprises a compromise between architectural and engineering criteria, that include function and aesthetics, as well as material properties, forces amount and distribution, and members' deformations under loading respectively. In the second case, the final equilibrium form of the structure results from the elastic deformability of the members and their residual stresses that accumulate throughout the deformation, i.e., form-finding process.[6] The specific structural typologies comprise milestones in architectural technology and engineering development in the early 1970´s. At the same time, they established new frame conditions and methodologies for interdisciplinary design and numerical analysis, as well as the actual erection process applied.[7]

Both projects are representative of the development of lightweight and natural structures, as well as the study of form-finding and self-formation

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processes that set-up the background for the creation of lightweight, mobile and adaptable architecture. To this end, Frei Otto himself established a broad spectrum of concepts based on membranes, cable-nets and retractable roofs, umbrellas, arches, gridshells, branching and convertible pneumatic structures. Frei Otto's architectural values, and the syntax of design adopted, is today more relevant than ever. Enhanced through technological developments in digital parametric design and numerical analysis processes and simulations, as well as advances in materials and control engineering, transformable structures are, in the meantime, conceptualized and developed based on the philosophy inherited on form variation, structural lightness and low footprint. They encompass sustainable features at micro and macro level of operation (i.e., kinematics, structure, building and city).

The presentation of the Olympic Stadium in Munich and the numerical analysis process developed as well as the Mannheim Multihalle typology and erection process, highlight main principles shared with the subsequent development of transformable structures in architecture. These structures feature increased flexibility, controllability, minimum complexity and energy consumption during operation. Most importantly, the foundation laid by Frei Otto through the development of lightweight, adaptive structures allows for further optimization in the design of transformable structures that may respond to external stimuli. In this framework, consequent saving of material provides corresponding reduction of the environmental impact of the structures' development and operation. Energy efficient actively controlled transformable lightweight structures to be presented provide a related framework of emerging architectural-engineering solutions.

FREI OTTO

Frei Otto (1925-2015) was a pioneering German architect and structural engineer, renowned for his innovative lightweight and tensile structures. Born on May 31st in 1925, in Siegmar, Germany, Frei Otto was initially trained as a stonemason. After the 2nd World war, Frei Otto studied Architecture at the Technical University of Berlin from 1948 until 1952. In the same year of his graduation, Frei Otto founded his own architectural office in Berlin. He earned the degree of Doctor of Civil Engineering at the Technical University of Berlin in 1954. His dissertation 'Das Hangende Dach, Gestalt und Struktur' was published in German, Polish, Spanish and Russian. Frei Otto's architectural work was lightweight, open to nature, low-cost and in some cases, even temporary. In 1954 he initiated collaborations with Peter Stromeyer at L. Stromeyer & Co. In 1955 they designed and built lightweight minimal temporary structures made of cotton fabric for the Bundesgartenschau in Kassel, Germany. These were his first works to gain national recognition.

In 1958, Frei Otto founded a small private institute dedicated to lightweight structures, namely, the Institute for Development of Lightweight Construction, and opened a new studio in the Zehlendorf district of Berlin. Over the next five years, he taught periodically in the United States, taking on visiting professorships at Washington University, Yale University, University of California at Berkeley, the Massachusetts Institute of Technology and Harvard University. In 1964, he established the Institute for Lightweight Structures (IL) at the University of Stuttgart (in 2001 renamed to 'Institute for Lightweight Structures and Conceptual Design' (ILEK)). This became an academic center for research and innovation in lightweight tensile structures.[8] He served as director of the Institute until 1991. Thereafter, he received the title of emeritus professor. In 1969, he founded his own practice, the Atelier (Frei Otto) Warmbronn architectural studio in Stuttgart. In his atelier, Frei Otto and his collaborators dealt with the development of highly effective structures of minimum material.[9]

Frei Otto's work highlights the adoption of natural forms in conjunction with a strong focus on sustainability. Already in the mid-1950s, Frei Otto was concerned with exponentially growing cities and related issues of human settlement and mobility. He

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researched 'mobility', 'growth and change' and 'adaptability and flexibility' in expanding urban context. In 1974, his Institute for Lightweight Structures (IL) organized an international colloquium on adaptable architecture. An expanded report of all contributions to the thematic by the attendants (architects and engineers, physicians, biologists and sociologists, ecologists, politicians and historians from 10 countries) was published with the title 'Anpassungsfähig Bauen' (Adaptable Architecture).[10] Key terms introduced in this colloquium, reflect different dimensions of adaptable buildings, such as changeable, demountable, reduction, energy-building, reusing, flexibility and user planning. Pioneers in the area who participated in this colloquium included Yona Friedman, Bodo Rasch, David George Emmerich and Konrad Wachsmann. Frei Otto's concept on adaptable architecture was strongly influenced by related studies conducted by Konrad Wachsmann, which referred to the industrialization of construction.

Frei Otto investigated and determined the optimum shape and behavior of lightweight structures through physical models. He received numerous awards and honors, including the prestigious Pritzker Architecture Prize in 2015, awarded to him shortly before his death on March 9, 2015. Frei Otto's legacy continues to influence architects and engineers around the world, inspiring greater emphasis on lightweight construction and sustainable design.

OLYMPIC STADIUM IN MUNICH

The implementation of the awarded competition design of the Olympic Stadium in Munich in 1972 epitomizes a utopian vision, blending elements of the characteristic design flows of the 1960s. The project had a focus on developing an 'urban landscape' (Figure 1).[11] Following the first prize architectural competition award to Behnisch and Partners with Jürgen Joedicke in 1967, Frei Otto and his collaborators worked at the Institute for Lightweight Structures (IL) at the University of Stuttgart on tensile solutions through model studies for the realization of the project. The lightweight structure of the Munich Olympics-Arenas comprises the first architectural-engineering design of long-span cable-net structures. The design's realization marked a milestone, as it involved the first large-scale computer applications. The Finite-Element method was originally expanded and applied for the design, development and analysis of the structure, rendering the realization of the original 'architectural vision' possible.[12]

The design of the lightweight cable-net structure primarily referred to the process of form-finding that best satisfies the loading and material-specific conditions based on the design concept. In principle, form-finding comprised an iterative process, an optimization, rather than a commitment to a specific form of structure. The analysis approach had to be carried out computationally, due to the complexity of the system, the boundary conditions and the accuracy requirements.[13]

The prestressed net was studied through iterative geometrical nonlinear elastostatic analyses. The structural form was, at first, approximated in experimental models that were digitally registered and then numerically improved interactively. In general, the origin refers to a planar net that is prestressed between fixed points. The fixed point's position is then altered vertically, so that the net obtains a spatially curved shape. The analysis is nonlinear due to the geometrical modifications of the system, and the equilibrium form of the prestressed net is iteratively investigated for every displaced state of the supports. Thus, the procedure refers to a numerical simulation for a stepwise hanging of the net from the origin plane (Figure 2). The design and analysis considered the entire transformation process, from the planar to the form-found state.[14]

MANNHEIM MULTIHALLE

Following comprehensive investigations conducted by Frei Otto and his collaborators at the Institute for Lightweight Structures (IL) at the University of Stuttgart, on elastic gridshells,[15] the prototype

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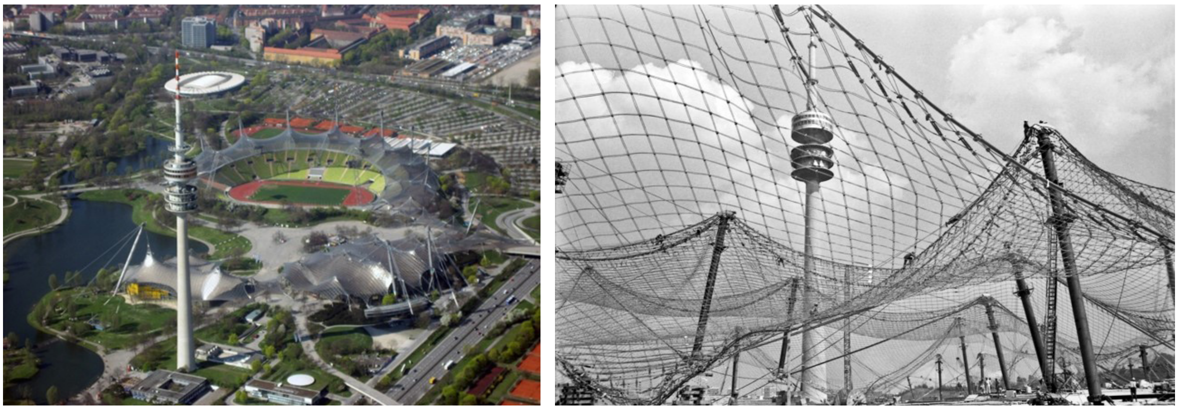

Figure 1. The Olympic Stadium of Munich, 1972, and detail view of the cable-net during erection.

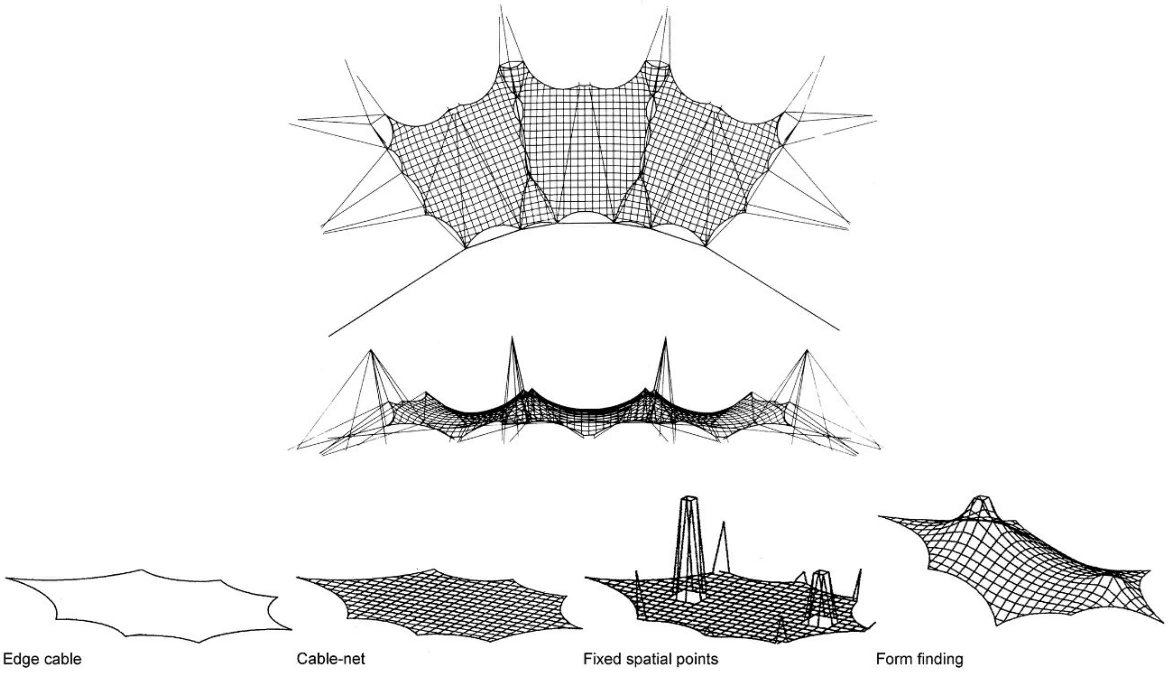

Figure 2. Analytical form-finding of lightweight structures based on the Finite-Element method: east tribune (above) and principal approach (below).

structure of the Manheim Multihalle was constructed in 1975. The building consists of a 9000 m^2 curved roof structure with a span of 60×60 m and mesh dimensions of 50×50 cm (Figure 3).[16] The competition for the corresponding masterplan of the Herzogenried ark with the Multihalle referred to the Bundesgartenschau that took place in Mannheim in the same year of the building completion. The preliminary design by the winning architects (Mutschler & Partners architects and Eckebrecht landscape architects) aimed to blend the park areas with the natural hilly landscape using architectural means. The Multihalle project showed that strained gridshells enable adaptation in form, solely based on the geometrical and mechanical properties of the structural members. The structural shape was approximated through modelling of its funicular using delicate chains, and in different scales and preciseness in the construction. The structural members were transformed from the planar to the form-found state of the system in its actual erection process.

The structural members consist of pairs of timber laths with 50 mm cross section and lengths of up to 6 m. These were joined in the factory into lengths of 30-40 m. The structure was assembled on the ground and bent from the planar to its target shape based on the ‘push-up’ technique. A scaffold tower system of 9×9 m spacing was implemented with timber spreaders to distribute the loads. The towers were jacked up in 33 cm space intervals with extra sections being added in. When the grid was lifted to give sufficient headroom, forklift trucks were used to both lift the towers and to move the bases to keep the towers vertical. The adjustment of the structure in its final position was made before the edges and joints were fixed, by bracing from below with air-supports. In this way, sagging of the structural members between the scaffolding towers could be eliminated. The final stiffening work involved pairs of diagonal wire strands interconnecting every sixth joint and bolt connections tightening with disc springs and plain washers at the cross joints.[17] Any other erection method, e.g., the lift-up technique, would have required very large cranes that would have to remain on site until bolting up was completed.

The project demonstrated that the use of elastic materials for the structural members may comprise the driving agent of their design and erection process. Furthermore, the same straight and planar elements can be used for different curvatures, whereas the determining criteria correspond to the individual form-found state of the system, comprising part of an open-loop process of development.

CONTEMPORARY TECHNOLOGY

Based on the example of Frei Otto’s integrated interdisciplinary approach, the design and development of lightweight structures, of both rigid and elastic members, require interdisciplinary performance-based design processes. These adopt digital design and numerical analysis in following open-loop processes of investigation and development. Throughout the development and optimization process, advanced computing and performance simulation methods may provide meaningful visualizations of the digital design and numerical analysis models. At the same time, advances in material design and kinetics enabled the development of transformable lightweight structures. Related individual engineering precedents in the area have gained mostly from an integrated architectural engineering design approach already at the stage of the conceptualization of the systems. The approach refers to the structure composition, stability, kinematics and operation with regard to the energy performance of the actuation system.

Driven by aspects of global energy consumption, financial instabilities and humanitarian crises, together with ever more noticeable consequences of global demographic growth, as well as large migrations and threatening decrease of natural resources, the demand for lightweight and efficient transformable structures is even more prominent today. Lightweight structures in the future will not only enable minimization of the materials’ volume and weight, but also of the embodied energy and

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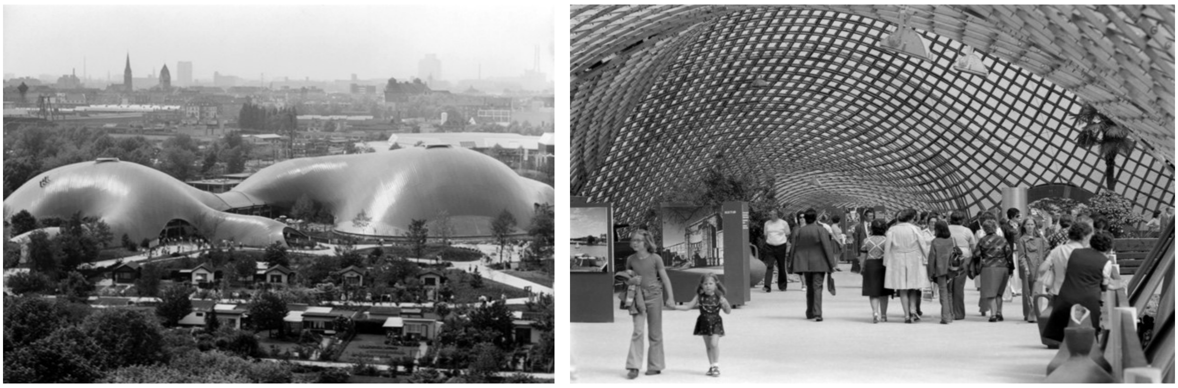

Figure 3. Mannheim Multihalle, 1975: Aerial perspective and interior view.

the development of recycling-friendly construction applications. Along these lines, the development of lightweight transformable structures aims at achieving affordable, advantageous and energy efficient solutions for our built environment. In achieving these goals, the following requirements are highlighted:

- Simplicity and flexibility should be maintained at structural typology level. Both requirements can be achieved through the employment of basic customized modular components to articulate any spatial system with controlled structural behavior and variable morphological features.
- Energy consumption for the required transformations of the structure should be minimized so that the kinetic system is effective and affordable. This aim can be achieved through minimizing the number of actuators and their use at optimal points within the structure. Furthermore, actuation members may be bundled, i.e., relate to single actuation components, and/or actuators can be detached from the structure body. In the latter case, minimum self-weight is preserved, since no actuators need to be moved about during the system reconfigurations.
- Simplicity and controllability should be ensured at the control mechanism level. This requirement is interrelated with the employment of actuators and impacts on the operation of the kinetic system according to the objectives, frequency and duration of the system transformations required in each application case.
- Flexibility should be facilitated in the kinematics of the system. This aspect suggests that an increased number of possible motion trajectories and target structural forms may be obtained. In this way, the structure can operate in an open-loop to respond to multiple changes that may occur throughout its lifespan. By extension, the structure is designed to further enable selection among feasible alternative solutions instead of a unique and fixed solution.

In exemplifying the above-mentioned aspects in the design of lightweight transformable structures, three examples are briefly presented. These examples share characteristics of actively controlled lightweight structures that take advantage of their transformability to optimally adapt to the external loading conditions through enhancement of their structure performance or modification of their form. In this context, adaptiveness refers to the active manipulation of both, the stress fields or deformations within the structure and the topological configuration of the system.

At the kinematics level, maximum flexibility within the form-finding process may be achieved through linkage-based modular systems. Such systems comprise continuous series of rigid bars interconnected by secondary members to provide the spatial system. They provide enhanced shape flexibility and controllability. This class of multilink structural typologies has certain similarities to the experimental small-scale prototype models developed by Frei Otto aiming at the form-finding simulation of lightweight structures by physical means.

Transformability of a planar linkage structure requires implementation of brakes (e.g., electromagnetic, pneumatic, or hydraulic brakes) on the joints of the rigid bars. These brakes may be released for the purpose of reconfiguration. Thus, multiple structural forms can be obtained through respective adjustment of the joint angles using actuator devices integrated onto the structural joints.[18] To avoid the installation of multiple actuators on the joints, a multistep reconfiguration procedure has been proposed by the authors. In each step, only a specific number of joints of the system is released and one joint angle is adjusted.[19] Subsequently, the joint already adjusted remains locked. The process concludes when all the joints are adjusted. Once the target form of the structure has been found, the actuator locks in place by applying all the brakes. This approach requires a minimum number of actuators (e.g., one linear motion or rotational actuator) positioned at the ground supports of the main linkage structure.[20] In maintaining control simplicity to the spatial structures domain, the kinematics concept is applied to planar systems that may be serially or radially interconnected to provide spatial rectangular or circular structures in section.

An application example of the basic kinematics concept refers to a circular section structure that consists of active radial planar linkages and passive peripheral connecting elements of adjustable length. The active radial planar linkages are pin supported on the ground as well as on a telescopic column at the middle of the spatial circular section structure. The column may extend along the vertical axis of the spatial system. Three different shapes optimally obtained through the kinematics concept refer to a paraboloid shaped spatial structure, a quasi-ellipsoid one and a nonsymmetrical aerodynamic one of same span and different height (Figure 4).[21] Comparative numerical studies of the structural response against wind and snow loads suggest that the transformability of the structure is critical as a means of enhancing its performance (i.e., minimizing internal forces and displacements) under external loading. Even with a negligible modification of the structure's shape in terms of architectural functionality, the wind performance of the structure may change significantly, thus providing great potential for system optimization.

The SmartShell was built in 2012 at the University of Stuttgart campus in collaboration with the Institute for Lightweight Structures and Conceptual Design (ILEK), the Institute for System Dynamics (ISYS) and the engineering firm of Bosch Rexroth. It is a lightweight adaptive shell structure with significantly less self-weight than what is needed to support the actual external loading (extreme snow and wind loads) of the structure (Figure 5).[22] The shell consists of cross-laminated wood slats constructed in four layers of 40 mm total thickness and is hinge supported at its four corner points on the ground. The fibers direction is set diagonally between the supports, in alternating direction between the layers. The structure's span amounts to 10 m and its height from the supports is 3.57 m. Thus, the structure has a thickness/span ratio of 1:250, constituting the thinnest load-bearing wood shell of similar size built up to date. Three supports are equipped with hydraulic actuators that enable spatial movements of the system within a fraction of a second to counteract and reduce stresses and deformations under static and dynamic loads as well as to dampen vibrations.

Through its active control mechanism, the structure is capable to counteracting external static loading in preserving homogenization of the resulting stresses and reducing respective peak values. The structure can also counteract dynamic loading through provision of damping to the system, and it therefore minimizes the risk of material fatigue and increases its life span. Consequently, optimization of the system refers to the highest possible

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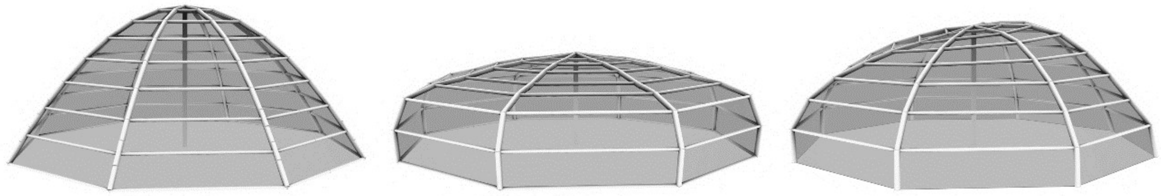

Figure 4. Different possible shapes of the spatial circular linkage structure: the paraboloid (left), the ellipsoid (middle) and the aerodynamic shape (right).

Figure 5. SmartShell experimental prototype with actuators integration on three supports at the University of Stuttgart campus in 2012.

reduction of the structure's material enabled through its active control. In comparison with a conventional design, the potential savings in material achieved with the SmartShell amount to more than 70 %.[23] In addition, the adaptive control concept may further improve the serviceability and robustness of lightweight structures.

In the broader sense of actively controlled adaptive structures, the 'Demonstrator, D1244' at the University of Stuttgart refers to a slender 12-storey steel structure that serves, since 2021, as an experimental prototype for several research projects conducted by 14 Institutes at the University of Stuttgart and three non-university institutions, all under the chair of the Institute for Lightweight Structures and Conceptual Design (ILEK). The interdisciplinary project D1244 "Adaptive Building Skins and Structures for the Built Environment of Tomorrow" refers to a common architectural vision, namely the construction of the world's first adaptive tall building of modular and dismountable elements.[24]

The structure has a height of 36.5 m and a footprint of 5×5 m, i.e., slenderness ratio of 1:7 (Figure 6). The vertical circulation system and services of the building are decoupled from the actual adaptive structure. The primary tower consists of four units of three stories each that are diagonally cross braced on all sides. Twenty-four hydraulic actuators, responsible for the structure's control under wind and earthquake loads, are placed in parallel to the columns (i.e., inside the column hollow profiles) and in series to the diagonals (i.e.,

Figure 6. Demonstrator of the experimental prototype at the University of Stuttgart campus in 2021, and detailed view of the integration of actuators in a frame.

next to the diagonal elements). Independently of the external excitation of the structure, a different set of actuators is activated for the control purpose, i.e., reduce the resulting stresses and deformations of the elements under quasi static, wind loading and increase the damping of the system under dynamic, seismic loading.

The structure is controlled from a workstation housed in a container adjacent to the tower. Its control system incorporates 200 sensors, including strain gauge sensors and optical tracking encoders, strategically distributed within the structure. They serve as feedback information for the control system management of the actuators

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response. Different scenarios of wind and seismic-induced vibrations have been applied in testing the adaptive performance of the structure. A key focus of the design process was the optimization of the actuators placement and the minimization of their number, which is vital for reducing the operational energy of the adaptive system in achieving the corresponding structural performance. The iterative process of positioning the actuators alongside the design of the structural elements ensures optimal control of the system's response. In fact, active control methods result in lighter structures compared to passive control systems, which are activated only after the initial response occurs. Experimental results obtained so far demonstrate that this adaptive structure enables up to 50 % savings on structural steel, equivalent to more than 20 tons.[25]

CONCLUSIONS

This paper discusses aspects of structural transformability based on the foundations laid down by the architect and engineer Frei Otto. Key goals of his work addressed in general context, include aspects of form variation, minimum self-weight and footprint. In this frame, structural adaptiveness plays a significant role in any optimization process of the structural performance towards its environmental conditions on site. Two keystone projects carried out by Frei Otto in interdisciplinary environments of collaboration showcase the features of adaptiveness in the simulated form-finding and erection process respectively applied for the first time on an international scale.

Presently, relevant developments refer to actively controlled structures that respond to variable external nonconventional loading (e.g., wind, snow and seismic loading) through controlled transformability of their shape. Representative case studies presented herein demonstrate that structural transformability is achieved through the implementation of a control mechanism that may operate in a predefined way, or in an undetermined way according to the control objectives during the actual external stimuli. In both cases, the range of transformability of the system is defined at structural typology level, and its effectiveness, at the structural material and the actuation components implementation level. In this framework, a lightweight structure with minimum footprint and number of actuators detached from the structure body or implemented at optimal zones is mostly favorable in achieving minimum control energy consumption. Consequently, transformability in adaptive structures primarily depends on the material embodied and control energy, that need to be kept minimum for increasing its effectiveness, feasibility and affordance in real applications, as well as the range of structural shapes design. Even today, these aspects are consistent with Frei Otto's initial goals for the design of structures and are even more important and relevant for the creation of a sustainable and innovative built environment.

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[2] I. Meissner and E. Möller, *Frei Otto. Forschen Bauen Inspirieren* (Munich: Edition Detail, Institut für Architekturdokumentation, 2015). Frei Otto propagated the "natural form of architecture" as an expression of a modern, mobile, democratic and open-minded approach. His work was driven by a vision to create architecture for a peaceful society in harmony with nature. Thus, the development of lightweight structures was part of a broader architectural and socio-political ideology.

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[5] Cable-net structures comprise an additional development of tents of textile fabrics, based on the same principles of structural form. Like tents, cable-net structures consist of two basic elements: the tensile, load-bearing surface of the wide-meshed net consisting of cables and the compression mast or ground supports. Cable-net structures are stressed only in tension, they are flexible in bending and stabilized through prestress. Prestress is the obvious choice since no instabilities develop under any additional loading through compression, large deformations and flutter effects under external loading. Cable-nets of anticlastic shapes usually consist of two cable meshes that intercross each other and have opposite curvatures. The cable meshes are prestressed against each other and connected to flexible edge cables in bending that transfer the tensile forces to the masts and supports. The stiffness of the structure results from its geometrical conditions, i.e., double negative curvature, and the prestress of the cables.

[6] Gridshells were created in the search for a simple and economical lightweight construction for shell structures. Gridshells consist of bars with same cross section and standardized joints. All components are prefabricated individually or partly standardized and transported on site. Gridshells can be fast and easily erected, since they mainly follow a natural relaxation process in obtaining their final form. Different erection methods are possible beyond the initial 'push-up' technique applied in the Mannheim Multihalle 1975. These include the 'pull-down' and 'pull-up' technique, applied with scaffolding infrastructural support, cranes and ropes, or large inflatable balloons installed beneath the non-deformed grid. B. D'Amico et al., "Timber gridshells: Numerical simulation, design and construction of a full-scale structure," *Structures* 3, (2015): 227-35. Once the gridshell has adopted its final shape, the structure can be tightened by fixing all its joints and edge elements.

[7] F. Otto, *Tensile structures: Design, structure and calculation of buildings of cables, nets and membranes* (Cambridge: MIT Press, 1967).

[8] Juan Maria Songel González, "Frei Otto y el Instituto de Estructuras Ligeras de Stuttgart: una experiencia de sistematización en la búsqueda de la forma resistente" (PhD diss., Universitat Politècnica de València, 2005). https://doi.org/10.4995/Thesis/10251/2346.

[9] Juan Maria Songel González, "Frei Otto y el debate sobre la génesis de la forma arquitectónica," *EGA. Revista de expresión gráfica arquitectónica* 16, (October 2010): 176-83.

[10] B.Burkhardt, *Il14 Anpassungsfähig Bauen* (Stuttgart: Mitteilungen des Instituts für leichte Flächentragwerke (IL), Universität Stuttgart, 1975).

[11] J.Argyris and S.Kelsey, *Energy theorems and structural analysis* (London: Butterworths, 1960). The most influential aspect in the realization of the lightweight structure in Munich was the development and application of the Finite-Element Analysis method by John H. Argyris. PHOCAS, MC. Technology-driven design approaches to utopia. Stuttgart: Edition Axel Menges, 2017. John H. Argyris was the Director of the Institute of Statics and Dynamics of Aerospace Structures at the University of Stuttgart between 1959 and 1984, and subsequently Director of the Institute of Computer Applications at the same University from 1984 to 1994, which became one of the most renowned of its kind in the world. The most important contribution of Argyris' original research on energy theorems and structural analysis had been the matrix analysis methods for structures composed of discrete elements applicable in modern automated computation.

[12] The Finite-Element method enables computer calculations of any complex structures under general loads. The systematics of structural analysis using finite elements includes the following main steps:

- Fictitious division of the structure into small individual parts (finite elements).
- Mathematical description of the behavior of each of the fictional elements according to a behavioral pattern.
- Inclusion of the individual elements into a discrete mathematical model for the entire structure.
- Numerical determination of the displacements and stresses in the discretized structure as a result of the specified load.

The development of a general calculation methodology for the form-finding, statics and dynamics of tensile structures within the framework of the Finite-Element method, as applied for the analysis of the Olympic buildings in Munich in 1972, referred primarily to the appropriate formulation of the systems, the mathematical description of the elements behavior and the numerical response of the structure under external loading.

[13] However, a direct application of the numerical method based on the Finite-Element Analysis was not yet possible at the time of the project development. The theoretical fundamentals and new calculation programs with appropriate formulation and design of higher iterative analysis steps were developed in very limited time.

[14] Following successful completion of the numerical investigation of the lightweight structure of the Olympic Stadium in Munich, the research followed at the University of Stuttgart was related to an automatic form generation, including pronounced nonlinear problems in statics, dynamics, finite strains in elasticity and plasticity. In nonlinear elastic structures, progress was achieved with regard to the systems' static and dynamic stability under non-conservative loading. The conclusion of these research activities formed the basis for the subsequent development of a modern program system for nonlinear analysis of long-span cable-net structures.

[15] Ian Lidell, "Frei Otto and the development of gridshells," *Case Studies in Structural Engineering* 4 (December 2015): 39-49. https://doi.org/10.1016/j.csse.2015.08.001

[16] B.Burkhardt, *IL13 Multihalle Mannheim* (Stuttgart: Mitteilungen des Instituts für leichte Flächentragwerke (IL), Universität Stuttgart, 1978).

[17] Burkhardt, *IL13 Multihalle Mannheim*. To study the stability of the structure, the project's engineers of Ove Arup compared the numerical simulation of the load-deformation behavior of the structure with experimental testing of a model conducted by Frei Otto and his collaborators. Qualitatively, the two approaches reached the same results, but quantitatively the results differed considerably. For this reason, they could not be considered as mutual, independent controls. Nevertheless, in the specific case study, time was of essence, and costs would have been too high to prepare a proper computer program for the verification of the experimental tests.

[18] In principle, motion control of a planar linkage requires that the number of actuators equals the number of degrees-of-freedom of the system. For practical purposes, this means that multiple actuators would need to be attached to the structure, unfavorably increasing their self-weight as well as the energy consumption during reconfigurations.

[19] The number of released joints corresponds to the transformation of the linkage system to a 1 degree-of-freedom system during reconfiguration. In terms of kinematics, the basic mechanism corresponds to an effective crank–slider mechanism (i.e., a 1 degree-of-freedom system with a pin and a sliding support and one released intermediate joint together with a linear actuator), or an effective 4-bar mechanism (i.e., a 1 degree-of-freedom system with two pin supports and two released intermediate joints together with one linear or rotational actuator).

[20] The structure consists of 16 bars on each diameter axis, with 8 bars of 1.0 m length on each side of the central column. The diameter of the structure is fixed at 12 m, and the height of the paraboloid, quasi-ellipsoid and aerodynamic shape is 4.808, 3.153 and 3.972 m respectively.

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