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Structural and Physical Aspects of Construction Engineering

Shape Design and Analysis of Adaptive Structures

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Abstract

Architecture is mostly perceived as a static, unchanging and rigid element without an ability to react to the changing environment around it and the specific conditions of its location. The digital approach to architectural design has already shown that it is possible to create architectural prototypes that react to the external inputs by changes in their material properties or even in the shape. The conventional, stationary architecture is not able to react to the environmental factors, nor to the changing needs of building occupants, which brings architects, designers, and engineers to the issue of movement in architecture. This paper describes selected adaptive materials and structures used in architecture. An adaptive shape is designed and analyzed using a combination of 3D modeling tool Rhinoceros and the visual algorithmic plug-in Grasshopper, together with the extension for Grasshopper, Kangaroo. The wind simulation is made in the Flow Design.

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Keywords: Parametric Design; Environment; Smart Materials; Adaptive Structures; Grasshopper plug-in; Flow Design

1. Introduction

The potential of digital design tools is exploited to a large extent to examine possibilities for developing of progressive architectural shapes and structures. Computer simulations can determine the energy consumption, the optimization of the material and therefore the overall form of the architecture. The architecture of tomorrow might be able to morph as a reaction to the changing live loads or environmental fluctuations. The change itself can happen in the structure of the material that is exposed to the effects of the environment, or in the overall architectural form.

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2. Shape changing smart materials

2.1. Adaptability in nature

Nature provides great examples of short-term adaptations to the environmental changes. Tree cones, for instance, respond to the changes of relative humidity in the air [1]. Tree cone scales are folding when dried to release seeds, while in the wet environment, the scales close-up.

2.2. Smart materials – shape changes influenced by changes in humidity

The adaptive mechanisms in nature, especially the hygroscopic properties of wood, are a great inspiration for designers and artists in their responsive designs. Achim Menges Architects have developed a climate responsive pavilion called HygroScope [2]. It is made of thin wooden sheets with a different grain directionality. The installation is responding, without any use of additional technology, to different levels of humidity in the air by slight changes in the inner structure of the material (Fig. 1).

The properties of the responsive wood that can support the circulation of humid air in its environment were verified in the project called Loop [3]. By designing a suitable shape and the spatial organization of the wood paneling using a computer simulation, the authors were able to achieve a much higher performance of the air circulation (Fig. 2).

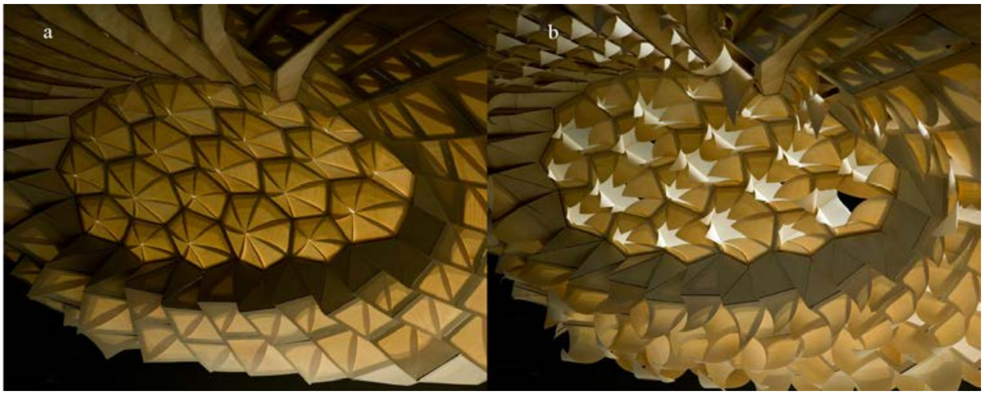

Fig. 1. (a) Closed apertures by high environmental humidity; (b) Opened apertures by low environmental humidity.

Fig. 2. Shape design of the climate responsive pavilion.

2.3. Smart materials – shape changes influenced by changes in temperature

Design studio Roosegaarde used smart Mylar foils to create an installation called LOTUS 7.0 [4]. The material belongs to the group of SMA (Shape Memory Alloys) and reacts to the temperature changes. Roosegaarde designed a hemispherical shape covered with petals (made of foils) that can sense the presence of the visitors, which triggers the lighting input to the lamps and their heat causes the shape changing of the foils (Fig. 3).

Translated Geometries (Fig. 4) is a project from the IaaC in Barcelona. The authors created a shape-shifting structure responding to environmental cues, using the SMP (Shape Memory Polymer) for joints. Thanks to the flexible joints, the structure can react to the heat input and contract and extend again using a folding principle inspired by Origami pattern. If the material is heated above 60-70 degrees Celsius, it changes its shape. Upon reheating, the material returns to its initial, static state [5].

Fig. 3. Temperature responding material used for the art installation in a church in France.

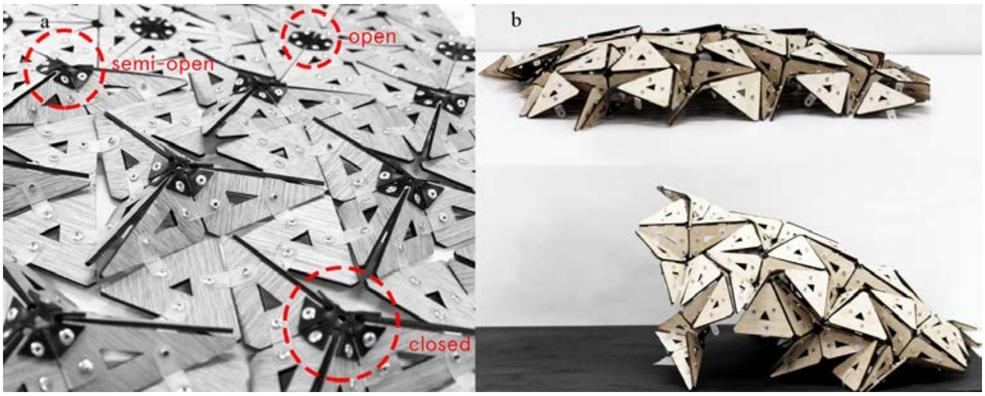

Fig. 4. (a) In red circles are the flexible joints made of the SMP; (b) Structure in its initial position and deformed after the heat input.

The changes in the inner structure of smart materials are reversible and can be caused by various factors, such as changes in temperature or humidity. The new research presents a multifunctional smart material that reacts to more than one factor [6]. The scientists used liquid crystalline networks (LCNs) and added groups of atoms that react to polarized light and implemented dynamic chemical bonds. The resulting material reacts to light, can remember its shape as it folds and unfolds and can heal itself in the case of damage when the ultraviolet light is applied.

3. Adaptive structures

3.1. Realized projects

Architects experiment with developing of adaptive structures such as kinetic surfaces or smart building envelopes that respond to the various stimuli, for example, movement of people, sun radiation and other [7 and 8].

Shiver House is a radical reinvention of the common Finnish Hut called mökki. The project is a kinetic structure which moves and adapts in response to surrounding natural forces [9]. Six hundred kinetic counter-weighted shingles are actuated by the wind, rain, and snow and rotate into a closed position which gives the pavilion a function of a shelter (Fig. 5).

Researchers from ETH Zurich have developed an adaptive façade that serves as a shading system and it is, at the same time, a movable photovoltaic system for electricity production [10]. The square modules, creating the structures are lightweight and flexible and can be applied on the façade of an existing building (Fig. 6).

Fig. 5. (a) The passive movement caused mainly by the wind; (b) Close-up of the kinetic mechanism.

Fig. 6. (a) Active solar façade – the first prototype was placed on HoNR Zurich; (b) Close-up of the robotic mechanism.

3.2. Prototypes

There are more ways how to design the mechanics of structures that are able to change their shape. The most common principle is the use of Origami folding. Such structure can contract and expand by folding and unfolding its faces enabling large deformations. Other ways include the use of active tensegrity systems or kinetic fabric structures.

Resonant Chamber (Fig.7) is a prototype of an interior envelope system that deploys the principles of rigid Origami. By folding and unfolding, the triangular structure is exposing its reflective or absorptive parts as a response to changing sonic conditions of the environment. The authors propose to use it as an acoustic ceiling in concert halls where it could transform the acoustic environment through dynamic, spatial, material and electro-acoustic technologies [11].

The deformation potential of fabric structures is explored in the project introduced at Venice Architecture Biennale 2014. Kinetic wall is an adaptive surface made of layers of elastic, translucent fabric. Behind the fabric, there is a grid of motorized pistons that are programmed to move in and out periodically to produce tensile stress on the fabric and thus the change in its shape (Fig. 8). There are no sensors involved, the structure moves as pre-programmed. However, there is a relationship between the visitor and the ever-changing space around him [12].

The system of active tensegrity enables small deformations in the structure and a better adaptation to the active loads. Luminous Cloud (Fig. 9) is a research project that combines smart materials and the use of the active tensegrity system. It is an interactive installation that responds to light and environmental stimuli. The materials used for the “skin” ensure the phosphorescent glow and the Shape Memory Alloys (SMAs) springs are embedded into the tensegrity system to react to the heat input [13].

Fig. 7. Resonant Chamber prototype.

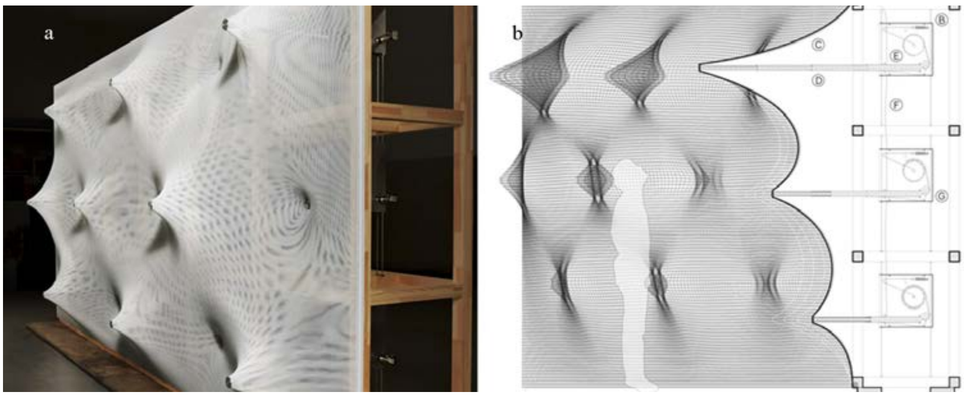

Fig. 8. (a) Kinetic wall prototype; (b) Scheme of the mechanism of motorized pistons.

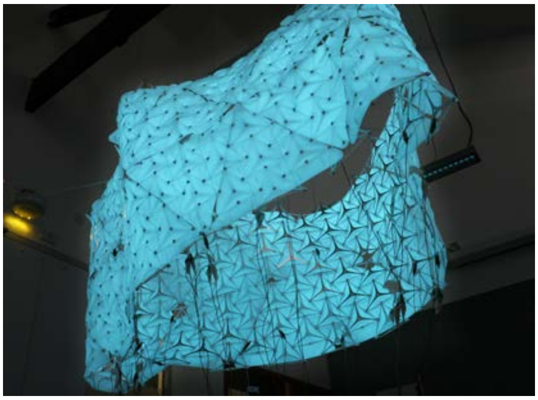

Fig. 9. Luminous Cloud installed as a flexible lighting system in an interior.

4. Shape design and analysis of an adaptive structure

4.1. Shape design

The realized projects, as well as prototypes mentioned above, show different approaches to the design of shape-shifting structures using either smart materials or principles that allow a change of the shape.

A reason for designing adaptive architecture is to ensure the best possible response to the environmental conditions. An adaptive tensile structure was designed (Fig. 10) and modeled in the software Rhinoceros.

The structure has an ability to change its form according to the prevailing load (Fig. 11 and 12). In the Kangaroo extension for Grasshopper, the geometry of the structure is mathematically defined and the basic material properties that represent a tensile material are set. Kangaroo, a live physics software, then simulates the change of the shape from folded to stretched and vice-versa.

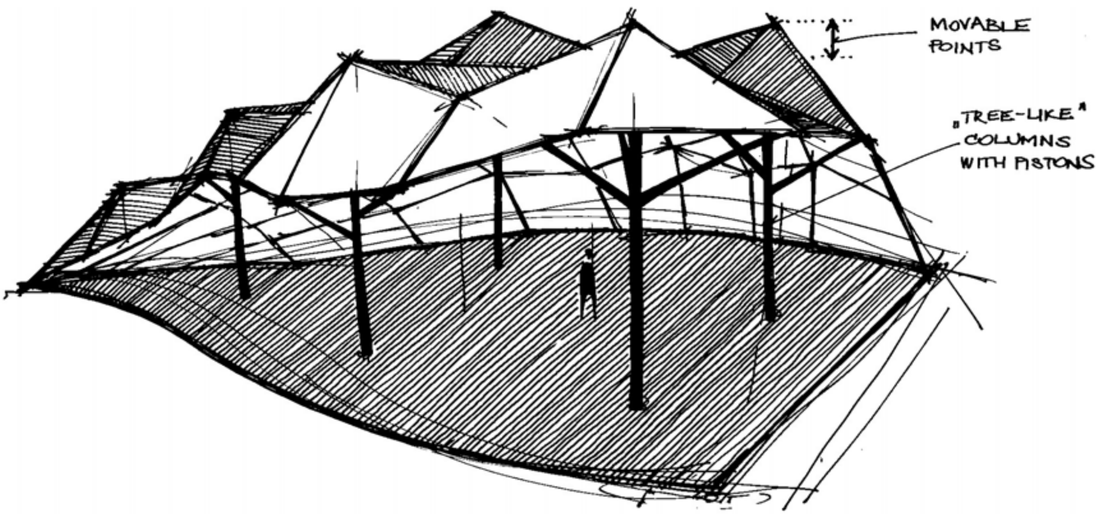

Fig. 10. Sketch with an idea of the adaptive structure with a transformable tensile roof driven by pistons.

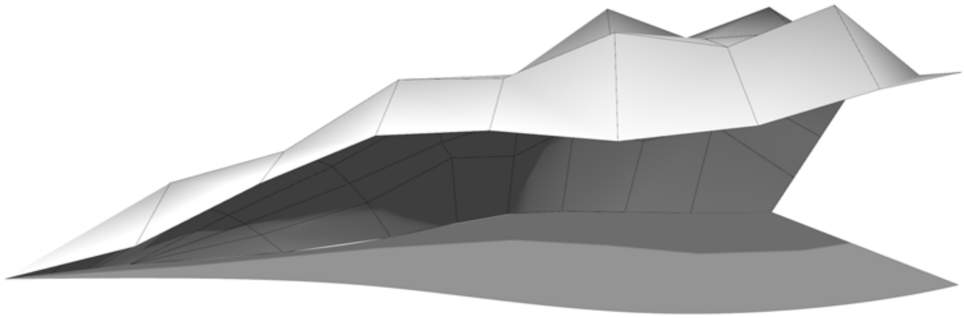

Fig. 11. 3D model of the designed structure in Rhinoceros.

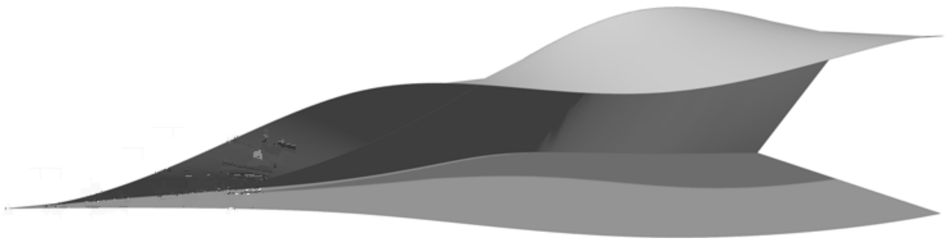

Fig. 12. The change in shape of the designed tensile structure.

4.2. Discussion

The designed structure has a stretched, smooth shape, in the case of the prevailing horizontal load and changes its shape to a folded form, to better respond to the prevailing vertical load. Pistons are being considered to be an option for providing the movement of the structure between the two positions.

A further analysis was made using the Flow Design software. Both shapes, smooth and folded, were tested for the wind drag coefficient. By the wind speed of 10 m/s and the wind flow that is parallel to the longitudinal side of the object, there is a difference in the drag coefficient of 0.15 (Fig. 13).

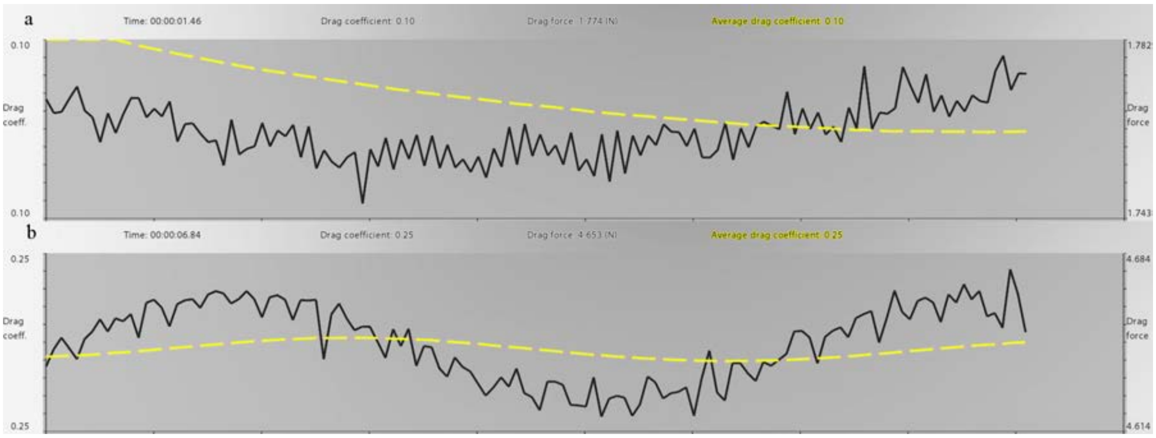

Fig. 13. (a) Graph from the Flow Design software showing the average drag coefficient for the smooth shape; (b) For the folded shape.

5. Conclusion

A short overview of selected shape-changing smart materials and adaptive structures was made to show different approaches in designing the architecture that is an active part of our environment. Many of the shown examples are developed as prototypes and they are still waiting for the application in the practice. However, if architectural designs should be sustainable, adaptive architecture that responds to the fluctuating environment and even benefits from it, can be the solution.

The second part of the paper is devoted to the designed adaptive structure and the analysis of the structure in the wind simulation software. The shape of the structure is designed to change from aerodynamic to folded and back which enables different reactions of the structure to different loads (prevailing horizontal or vertical).

The tensile structure was modeled in the 3D software Rhinoceros, simultaneously using the Grasshopper plug-in for Rhinoceros with the Kangaroo extension for live physics simulations. This design method allows to develop a desired architectural shape and, at the same time, to work with mechanical properties of the structure.

Both, the smooth and the folded shape of the structure were analyzed in the Flow Design software. The wind speed was set to be 10 m/s and the wind direction was the same for both of the models. The adaptability of the tensile structure allows the change of the shape in case of a strong horizontal load and thus a better response to the wind pressure. The difference in the drag coefficient is 0.15, after the shape is changed into smooth.

The ability of the designed structure to change its shape allows it to benefit from the changed shape while different external loads are acting on the structure. The structure will be developed further and tested.

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