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DESIGN AND SIMULATION OF AN ACTIVELY CONTROLLED BUILDING UNIT

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ABSTRACT

Conflagrations often lead to catastrophic phenomena in several countries across the globe during the summer period. Such phenomena advocate for multidisciplinary research activities including on- and off-site investigations of data-collection and evaluation as well as event-based virtual scenarios and action solutions respectively. In this framework, a temporary building unit is proposed to host single researchers in remote environments. The unit consists of a lightweight structure that can be easily erected and actively controlled. The unit is supported on four diagonals anchored to the ground and it has a circular horizontal and an elliptical vertical section. The core consists of a glass-fiber polymer (GFRP) cone base at its lower level, vertically positioned GFRP bending-active strips and a GFRP cone at its upper level. The cones are vertically connected through tendons that are activated by linear motion actuators. The structure consists of a double layer gridshell of GFRP bending-active rods and a semitransparent ETFE membrane with embedded thin-film CIGS photovoltaics. Sensors on the membrane transfer continuously the external wind pressure to a control system for the adjustment of the spatial shape of the unit through the tendons. The paper displays the design of the unit in its components, and emphasizes on its adaptivity features with regard to the structural deformability in parametric associative design logic. The methodology followed serves as a basis for further iterative analyses with regard to the form optimization of the structural elements, the system's load-deformation and dynamic behavior.

KEYWORDS

Temporary building unit; bending-active members; gridshell envelope structures; active control; adaptive structures.

1. INTRODUCTION

In remote areas with limited recourses supply and hostile external environmental conditions, living conditions need to be supported by an architecture of temporary, minimum spaces that enable well-being and safety. In this context, examples of effectively implemented research units constitute polar stations in the Antarctic, like the Neumayer III supported on liftable columns in the deep ice surface, the Princess Elisabeth founded on bedrock and considered as zero-emissions building unit, and the Halley VI composed of individual raised semi-autonomous prefabricated modules (British Antarctic Survey, 2005; Hartwig et al., 2006; Sanz Rodrigo et al., 2007). Technology may further support the development of related building units in achieving sustainability of the natural and built environment through an architecture that features easy transportation, assembly and disassembly, modularity, lightweight, flexibility and adaptiveness to changing functional, external environmental and loading conditions. In particular, adaptiveness describes the process with which an organism gains larger identification to its environment. This may be achieved through modifications in its structure, or its function through behavioral, anatomical, or physiological processes that favor the possibilities of its survival.

In the past decades, features of adaptiveness through a high degree of flexibility played a vital role in a number of architectural experimentations aiming at an improved and sustainable future of the built environment. These aims were meant achievable by respective technological advances, primary enabling industrialization and mass production. The Dymaxion House by Buckminster Fuller in 1945 dealt with a mobile assembled housing unit that could be located in any area. Lightweight industrialized components were used that could be easily assembled on-site (Kronenburg, 2007). The mobile housing unit by Reyner Banham in 1965, named as 'Transportable Standard-of-Living Package', featured adaptiveness based on its capability to be included within different spatial conditions (Spiller, 2006). In addition, the usage of electric panels on the unit's envelope served the provision of energy required for its autonomous operation for independence from other infrastructures. Conceptual explorations by Archigram were interrelated by a number of mechanically, electrically and cybernetically controlled systems (Cook, 1999). The designs consisted of a primary skeleton structure that also carried the mechanical services, and expendable components, i.e., accommodation capsules conceived as industrial design objects, which could be clipped-on, or plugged-in, removed, or replaced from the main structure. In particular, the Living Pods, a concept by David Greene in 1966, dealt with the idea of increased mobility, adaptiveness enabled through flexibility of the interior open spaces and functionality in terms of housing. Although this capsule could be employed within a plug-in urban structure, or could be positioned in the open landscape, it was still envisioned to be a mobile 'house'. The project design could also be related to the Plug-in City project, a concept by Peter Cook in 1964, that dealt with the idea of prefabricated homes assembled into dense fluctuating urban patterns.

Similar concepts have been developed in the frame of a 'micro architecture' vision of buildings that are lightweight, mobile and ecological for the future (Horden, 2008). The structures served issues of mobility and adaptiveness to extreme environments. Through use of lightweight, high strength materials, low self-weight was achieved, as well as easy transportability. Examples like the Ski Haus, Peak Lab 02, PolarLAb, m_Igloo and the Micro Compact Home could be transported by helicopters, or even cars. The envelope structure of aluminum sheets and light-foam insulation could sustain extreme environmental conditions of temperatures, strong winds and snowfalls that prevail in the Alps. Furthermore, the House R-129 prototype by Werner Sobek in 2012, features adaptation to the internal functions and the external environment (Phocas, 2017). In the interior space, a central non-stationary module houses sanitary and kitchen installations. Around this central module various space-cells used for working and sleeping can be arranged. The unit's envelope consists of a plastic material of extreme lightweight and transparency. The structural frame is fabricated from carbon box sections. The skin has an electrochromatic foil, which prevents radiation of heat into the interior in summer and to the exterior in winter. The external surface of the envelope also carries solar cells applied by means of vapor deposition, which reduce light transmission by only 20 %, while supplying a large part of the electrical energy demand of the building.

From an engineering perspective, adaptiveness was initially favored through building mass reduction and high strength materials of relatively low elastic modulus. In this framework, Frei Otto translated natural solutions into architecture (Otto and Rasch, 2001; Finsterwalder, 2011); the coherent effects of bionics were analyzed and applied by technological means. Different physical models were used for the form-finding, such as soap bubbles and spring linkages. Aim was to provide minimum surfaces in tension and optimized shapes in compression. Part of the work applied was the development of pneumatic structures and shapes inspired by the behavior of physical pneumatic systems, such as bubbles and drops. Such physical structures have the particularity that their spherical shape is derived through the tractive forces that act on the wall surface.

An actual turn towards the realization of adaptive structures was achieved through transfer of active structural control concepts, at first place developed in aerospace, mechanical and structural engineering (Yao, 1972). At the same time, architecture was postulated as non-static, of having the ability to adapt in time changes through systems with embedded actively controlled kinetic mechanisms (Zuk and Clark, 1970). Active control concepts proposed were based on the ‘Variable Controlled Deformation’ method through application of stressing tendons within the structure. Along these lines, the definition of active structures was introduced for systems that involve active and static members, in order to support conventional design loads and extraordinary dynamic loads (Soong and Manolis, 1987). Research activities referred to active control systems of closed, open and closed-open loop, based on theoretical and experimental small-scale models (Yang and Soong, 1988). In all cases, adaptive structures require a feedback control system that includes sensors, as well as actuators for implementing the reconfigurations in response to the external input.

Reflecting on the development of adaptive building units, the current paper displays the design of an actively controlled unit and its components, and emphasizes on its adaptiveness under wind pressures (Ioannidou, 2022). The unit is proposed to temporarily host researchers in remote environments with high conflagration history and future risk. The next section presents the unit’s architectural development. The structure and the control components are exemplified in Section 3. Finally, the structural deformability investigated in parametric associative design logic, is presented in Section 4. The conclusions of the paper comprise Section 5.

2. UNIT DESIGN

The building unit that serves temporary accommodation of individual researchers, consists of a lightweight structure that can be easily erected and actively controlled (Fig. 1). The unit is supported on four diagonals anchored to the ground and it has a circular horizontal mid-plane, and an elliptical vertical mid-plane section with maximum diameter of 7.70 m. The pin-joint connections of the diagonals enable the erection of the unit at different topographies.

An open core area in the middle with diameter of 1.50 m hosts the vertical architectural elements and technical supporting systems including convector devices for heating and cooling support of the spaces and a water tank, while all functional spaces are arranged radially on the periphery between the core and the outer envelope (Fig. 2, 3). The entrance to the spaces succeeds through a circumferential corridor zone that acts as intermediate space with 60 cm width, between the core and the individual spaces of the unit. A metal escalator within the core, may be deployed to connect the ground with the main floor level of the unit. The effective storey height amounts to 2.10 m. The functional spaces are compartmentalized with integrated furniture that unfolds out of

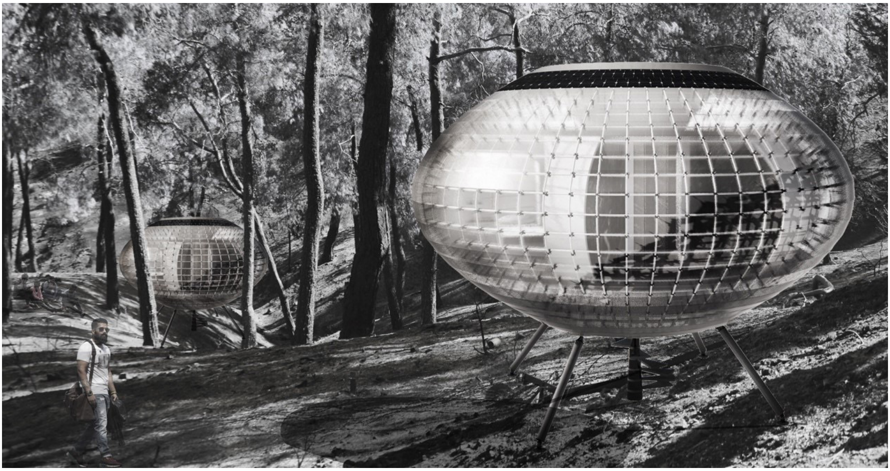

Figure 1. Building unit perspective in forest landscape

the radial inner walls, and covers the basic residential and remotely working needs of the user during the temporary stay on-site. Likewise, the bathroom and the kitchen are conceived as prefabricated elements with integrated appliances. Electricity is provided by thin-film CIGS photovoltaics embedded in the membrane envelope, while natural ventilation of the spaces is possible through horizontal openings in the floor and the roof of the unit.

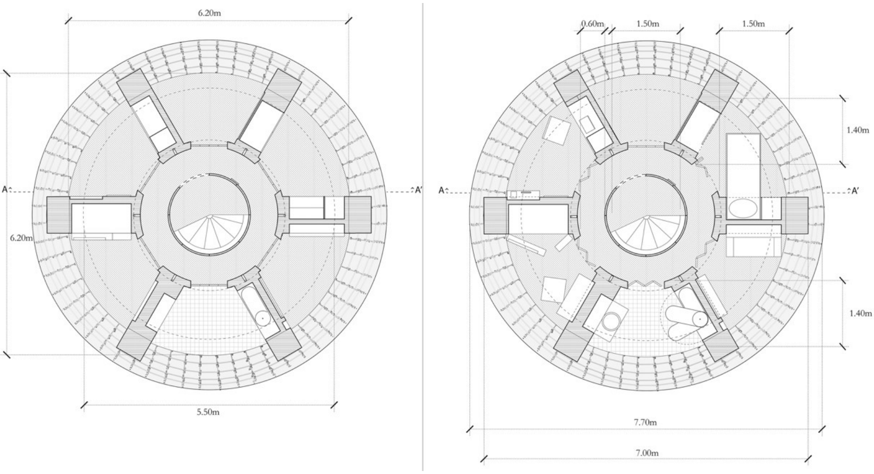

Figure 2. Floor plans in deployed and non-deployed condition of architectural elements

3. STRUCTURE

The primary structure of the building unit consists of the core and a double layer gridshell of bending-active rods arranged on the periphery of the spherical unit (Fig. 3). The gridshell supports an ETFE membrane with embedded thin-film CIGS photovoltaics. The structure is supported on four diagonals of hollow circular section of 150/20 mm dimensions that are pin connected at both ends and anchored to the ground to prevent uplift of the unit under wind pressure. The core consists of interconnected GFRP lamellas at the lower and upper level that form a conus shape, and GFRP strips along the height in between. The GFRP elements have a thickness of 12 mm. The lower and upper edges of the conus shaped lamellas support the gridshell over pin connections and are perimetrically interconnected through tendons, i.e., vertical cables with variable length. The lower tendons' connection succeeds over a pulley that is controlled in its length by a rotating actuator, i.e., stepper motor, arranged in parallel to the pulley.

The bending-active rods of the gridshell consist of GFRP hollow circular sections of 25/2.0 mm dimensions and are pin connected at the crossing points over double steel connection elements. Every third knot of the gridshell is provided with an electromagnetic brake to ensure moment-resisting connectivity of the layers during operation of the unit. The brakes are only released during transformations of the unit under wind pressure.

The horizontal floor and roof grids of IPE140 steel sections cantilever from the core, and are covered on both sides with polymere plates. The inner walls of 16 cm thickness are constructed as sandwich elements, with double heat insulation and outer polymere covering plates. They are provided with linear slots so that the tendons may have respective inclinations during transformations of the unit. The ETFE membrane is point fixed on the knots of the gridshell through strut elements and metal connectors.

Figure 3. Building unit's elements

4. ASSOCIATIVE PARAMETRIC DESIGN

The parametric design simulation aims at investigating the adaptive behavior of the structure under horizontal wind pressures. At the same time, the proposed process suggests the development of an associative parametric design approach that can easily move back-and-forward from the simulation outcomes to the initial parametric design intentions, providing an iterative feedback loop mechanism in the early design phase. The integration of parametric design and physics-based simulation into an iterative design approach is considered as an important element in the form-finding process, since the special nature of the structure, which consists of bending active rods in two directions, does not allow an accurate understanding of its adaptive behavior at the digital parametric design level only. The results obtained combine design intentions and corresponding structural performance verifications, offering first insight in the preliminary design of the structural system. Within the current research framework, the Rhino/Grasshopper parametric design environment and the live physics engine software Kangaroo are used based on a visual programming language (plug-in for Grasshopper parametric environment in Rhino 3D NURBS modelling software).

At first level, data on the direction and intensity of the wind in the specific area of study has been collected. The aim is to find the limits of wind velocity exercised on the surface of the proposed gridshell, in order to adjust its shape accordingly and at the same time, determine the design configuration limits that allow habitation of the interior. For this purpose, maximum and minimum wind velocity values have been collected together with their directions, which feed the parametric design process but also determine the limits of the adjustment envelope of the structure. In a case study of the mountainous Limassol region in Cyprus that suffered severe conflagrations in July 2021, the average maximum wind velocity for each month does not exceed the value of 15 km/h. This information is used as input data in the parametric control phase (Fig. 4), whereas the wind velocity, V [m/s], is related to the wind pressure, P [N/m^2], acting on the building unit as follows:

$$P = 0.613V^2$$

The visual programming process that includes geometric development and parametric control as well as physics-based simulation are formulated into two basic

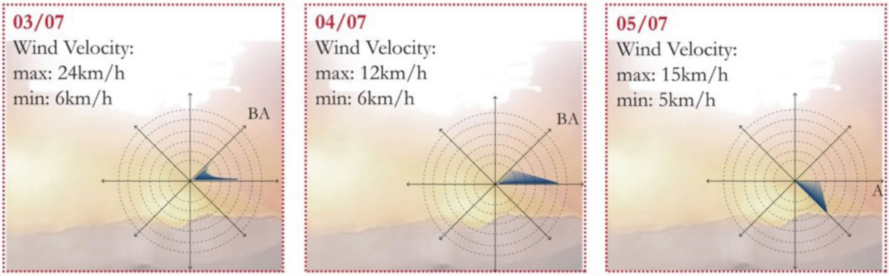

Table 8. Average results and characteristics characteristic results of the tensile test on basalt FRP rods. Source: (Riga Technical University 2019)

distinct steps. The geometrical classification as well as the physical behavior simulation are conducted simultaneously, in order to achieve an optimum adaptive control of the overall shell system. Therefore, the parametric classification of the geometry considers the physical properties of the materials applied. The parametric simulation focuses on the primary gridshell structure, whereas the inner walls and furniture are considered as static elements in the digital environment of Rhino software.

In the first step, that of geometrical development and control, the gridshell is modeled based on three concentric circles with diversifications in Z position. The lower circle, with radius 1.65 m, is fixed and is anchored at the bottom in contact with the four supporting legs of the structure. The middle circle, with radius 3.86 m, is 2.2 m higher that the first one. The third circle is raised 2.05 m above the second one with initial radius of 1.65 m. The parametric development of the latter circle allows control in all directions and angles of rotation (X-Y-Z rotation transformations), in order to response to all scenarios under investigation, but also, to allow transformation reaction of the gridshell in all wind directions. The height and radius of differentiated circles are used to develop a final surface, which is then converted to a mesh and consecutively to a quad remesh system with specific quad remesh settings. In short, the main inputs refer to target quad count with value 360 and include no symmetry in X-Y-Z directions. This allows flexibility with regard to the shape of the quad mesh, producing regular quad faces in all cases of change of the original shape. The final quad mesh includes 351 faces representing respective cells of the gridshell structure. The first step leads to the development of a two-sided conical elliptical shape that is used as the starting point for physics-based simulation and in turn, allows the form-finding of the gridshell under development.

In the second step of the proposed algorithm, the edges of the provided quad mesh are classified as the bending-active rods of GFRP, comprising the overall gridshell in two directions. The bending-active rods are parametrically associated with the rotation deformations that occur in the parametric control step of the algorithmic process. Also, they are physically encoded based on Goals of Kangaroo2 physics-based engine (in previous version of Kangaroo Goals, called Forces). The Goals include Angle (previously Bending), Load, Length (previously Spring), On Curve and Anchor.

The GFRP bending-active rods of the gridshell are firstly classified in two directions by using the WarpWeft component that separates the edges of a mesh into two lists according to the Warp and Weft direction. In each direction and through a parametric procedure that classifies individual continuous edges, this geometrical info is used as input in the Angle component for bending behavior simulation. The Goal 'Angle' involves Line A and Line B but also Rest Angle and Strength inputs. The main goal is to maintain the Rest Length value, regardless of the angle ratio formed between continuous lines, a goal that refers to active bending behavior. In addition, the Goal 'Length' is applied, to maintain the original length of the edges, a behavior which refers to the so-called spring behavior on the basis of Hooke's Law of elastic stress-strain behavior (Ahlquist and Menges, 2011). In this case, the inputs of the initial lengths of the edges as well as the final ones remain the same, which achieves the simulation of the sections as rigid elements without changing their length.

Additionally, the Goal 'Load' is applied as part of the Kangaroo simulation process. Specifically, Force Vectors that have a vertical direction in relation to the surface of the grid and start from each vertex of the quad mesh are inserted as input to the specific component after mesh deconstruction via the Deconstruct Mesh parametric component. Then, the points of the quad mesh in the lower circle are anchored via the 'Anchor' Goal, keeping the bottom part of the gridshell at a fixed position. Finally, group of points at the periphery of the gridshell, four in each quarter of the structure and one in the upper circle, which is subject to continuous deformation, are formulated. The goal is to use the different group of points as input in combination with corresponding curves in the OnCurve command, in order to keep points on given curves based on each distortion of the overall gridshell. Final step in physics-based behavior encoding is the introduction of all Goals in the Kangaroo Solver component as a list of input data, allowing the calculation and the execution of the overall physical behavior (Fig. 5).

The investigation and control of the physical behavior of the overall gridshell in three dimensions is achieved in the parametric environment of Grasshopper through the parallel and dynamic alternation of the associative parametric geometrical components (i.e., specifically the transformation of the upper circle) and the form-finding process of Kangaroo, representing the kinematically active position of the entire system. For each respective alteration, the upper circle is rotated based on the direction of the wind, allowing bending of the respective edges in two directions but also pulling of the shell, in order to capture the deformation of shape. In order to evaluate the results obtained and to verify the accuracy of the physics-based behavior against the initial gridshell geometry, a comparison between the initial and the final form-found surface is conducted, showing similar value results. This indicates that the structure after its deformation does not change in terms of the length of its elements but only in terms of its bending deformation preserving its initial surface area. Note that a longitudinal deformation of the module induces also a corresponding transverse deformation of the module. Figure 6 shows a series of bending alternations of the initial gridshell according to horizontal wind velocities. As it can be observed, there is a proportional distortion of the gridshell that is triggered by rotational transformation of the upper circle. When the horizontal wind pressure reaches 15 km/h the gridshell is deformed in its maximum state and the expedient indoor living space reaches a minimum height of 1.90 m.

Figure 5. The result of associative parametric design and an instance of physics-based bending behavior simulation of the gridshell

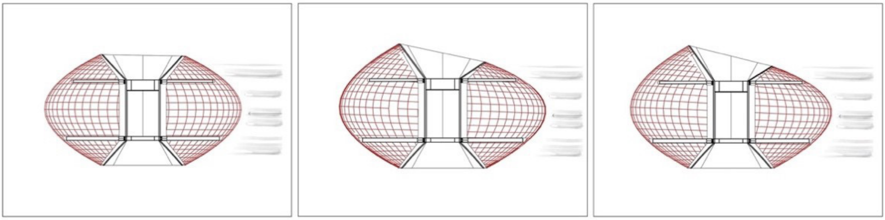

Figure 6. Characteristic bending alternations of the gridshell. Left: Wind velocity value (0.1 km/h) – height of interior space value (2.10 m), Middle: Wind velocity value (10 km/h) – height of interior space value (2.00 m), Right: Wind velocity value (15 km/h) – height of interior space value (1.90 m)

Consequently, the applied physical behavior enables the adaptation of the gridshell in different environments with different wind pressures. Also, the associative parametric design and control of the initial shape allow its modification and adaptation according to various spatial and metric changes of the original geometry, in order to adapt to the respective functional needs. The simultaneous investigation in a single parametric design environment enables the real time control and dynamic correlation of both, the design and the behavioral simulation results. The methodology followed serves as a basis for further iterative analyses with regard to the form optimization of the structural elements and the system's load-deformation behavior under permanent and variable loads combinations, as well as the system's dynamic behavior.

5. CONCLUSIONS

An actively controlled building unit has been presented in the current paper. The unit is based on a modular structure that can be easily transported and erected to host researchers in remote environments with high conflagration history and risk. The structure consists of elastic members that are interconnected through tendons, so that the external gridshell shape adapts to the wind pressures acting upon. The structural principles applied refer to the basic conceptual mechanism of active control initially introduced for providing adaptive structural deformation and stiffness features under varying external loading. The associative parametric design of the unit's behavior has provided insight in the deformation behavior of the system that may further provide an iterative feedback loop mechanism in the early design phase. Further development of the system in achieving autonomous energy efficiency, as well as the Finite-Element Analysis and experimental investigation of its load-deformation behavior are necessary.

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