RESEARCH

CONCEPTUAL SMART TEXTILE AND BENDING-ACTIVE ARCHITECTURAL MODULE

The case of Paços dos Duques de Bragança [2016]

Innovations in technology gradually contribute to the transformation and adaptation of man to society, as seen through the instant communication. Within architecture is not different. Traditionally static, architecture now brings technological advances and design concepts such as dynamics, transformation and adaptability to the reality of buildings. The term kinetic applied in this scenario is related to the current search for movement in architectural design, taking into consideration that one of the advantages of cross information is to solve many environmental problems and thus increase the level of sustainability. In this context, it is possible to observe a great potential in the integration of adaptive structural principles such as bending-active structures and architectural membranes, presenting a relation between complex shapes and resistance based on the behaviour of the material, taking advantage of lightweight and flexible composition to achieve complex shapes and geometries, providing regular actions. This work aimed a conceptual development of a structural solution involving a kinetic concept integrated with adaptive structures principles corresponding to bending-active and textile structures. The design of this structure is justified by the possibility of submitting a solution – corresponding to a module – which can be incorporated in new or in existing buildings, as to be applied to façades or roofs. The light and flexible material, corresponding to the structural principles studied, integrated into the movement generated by applying the kinetic concept, can result in a solution that provides an independent response in order to adapt to the environmental conditions such as wind, rain and sun, and the users needs, improving the functional performance of buildings and generating a unique appearance as a landmark. In order to apply the module developed as a real problem solution, a courtyard cover is designed for he Paço dos Duques de Bragança building in Guimarães, Portugal – great historical, architectural and cultural building – answering to the demand for increasing space for existing uses and also enable new uses.

Introduction

Design and technology advances aim to respond to the needs of ever-changing man through the search for form or architectural elements that have the capacity to adapt to the user needs and the environmental in an independent way. Therefore, kinetics in architecture is based on the application of various concepts such as dynamics, transformation and adaptability in buildings. Aligned with this concept, other long-standing structural principles in the historical context of constructions such as bending-active and textile structures have been studied and incorporated in contemporary constructions along with kinetic, taking advantage of light and resistant materials that make such structures. In what concerns to membrane architecture, the dynamism condition is an incident due to the condition of light and flexible constructions, since the lightness of these structures allows the application of mechanisms and automatisms[1]. The same theory can be applied to the bending-active structures. Including active bending in the structures leads to a wide range of structural concepts that owe their kinetic behavior to the elastic deformation of the members[2].

The motivation of the structure developed was based on the interest of understanding how technological innovations have created a new panorama in the scope of architecture and engineering, modifying the static behavior that for a long time characterized most of the constructions. Besides, stands out the understanding how the integration of other areas of knowledge, integrated with new materials and different structural principles considered special, can represent a scenario of better functional performance in buildings, characterizing a solution for the sustainable construction and rehabilitation so sought in the current context. The architecture liberation of basic functionalities for the human comfort seen during the Modernism forced to resort to the use of technology to generate heath, cold, light and ventilation, in order to make the spaces more livable, leading to a higher energy expenditure[3]. As a consequence, human needs of comfort become again an extremely important point in architectural design, with the term sustainability being increasingly linked to new construction, making it quite necessary to find ways to reduce the environmental impact caused by this industry, through combination of new materials and techniques that can actively respond to climate change in order to improve building performance without compromising user comfort.

Adaptive Structures principles

Basically, the adaptive structural principles applied depart from their concepts of the same historical origin – the nomadic societies. The means of inhabiting man and defending himself from the intersperses at this time was based on tents, where the closure normally made of animal skins characterizes the origin of the membrane structures principle and the interlaced and curved elements, usually using soft wood, serving of support for the animal skin, correspond to the origin of the bending-active structures principle. That inhabiting way of the nomadic people carries other concepts such as portability and movement, since these tents are characterized by being easily assembled and dismantled, as well as easily transportable, seeing that the ancient civilizations lived in constant displacement in search of food and means of subsistence, characterizing the first vestige of the kinetic in architecture. Nowadays, the three structure principles have been incorporated in buildings, mainly at the level of constructive elements.

Architectural Membrane

Also known as lightweight textile structures, architectural membranes can be seen as flexible and adaptive systems that adjust to different environments according to the necessities, e.g. responding to climate variations[4]. Targeting their environmental efficiency, the organic shape, the minimum weight, the high flexibility, the translucency, the fast installation and low maintenance are pivotal aspects to be considered for the new constructions and what justifies the designers more and more appreciate membrane materials. Apart from that, the architectural membranes are able to stand environmental factors and structural loads when compared to conventional materials with similar mechanical characteristics[5]. In an actual context where the use reduction of natural resources is mandatory and the renewal in the field of architecture and engineering is necessary, the architectural membrane are increasingly claimed as innovative concept of a light and sustainable material for construction.

Bending-active Structure

Active bending is the utilization of large elastic deformation to create curved structures from initially flat or linear elements[6]. This structure principle is understood as a system of flexural elastic deformation. The elements are formed by means of a controlled elastic deformation in order to obtain the desired geometry. This results in residual stresses of flexion in the flexed elements, also called pre-stress[7]. Introducing the curvature only during the assembly of the structure, limits it's pre-fabrication to creating the components, evidently simplifying the production and transportation. Besides, the reversible elastic nature of active bending deformation, entails an inherent component transformation that can in many cases extend the transformational capacity and reduce the complexity of kinetic systems.

Kinetic Architecture

Kinetics in architecture nowadays is a technological development as the basis of a constantly changing society that influences the evolution of contemporary architecture in the sense of greater flexibility and adaptation in response to the evolutionary process of man and the dynamism of his environment. This term[8] is characterized by having a very broad concept in the context of architecture, since it can encompass simultaneously several areas of knowledge such as structural, mechanics and electronics engineering, based on the design of buildings in which mechanized transformations of the structures aim to alter the shape of the building in order to meet the user needs in the interior and adapt to the external climatic conditions. Therefore, kinetic architecture can be defined as constructions and/or constructive components with mobility, location and/or variable geometries[8]. This architectural principle is also characterized[9] by the design of spaces and elements that can be physically reconfigured to respond to new needs, through which an adaptive architecture is formed. Even more can be constituted by a series of interconnected elements, such as structure, connections, actuators, materials and control systems, which constitute a dynamic transition structure.

The module

In order to develop a smart architectural structure – corresponding to a module integrating the architectural membrane, bending-active elements and the kinetic concept – the following main guidelines has been followed:

- Use of materials with structural capacity in order to resist the external actions and presenting low self-weight, also to achieve different shapes through a flexible behaviour;
- The structure may be incorporated into new constructions or rehabilitation/retrofit of existing buildings. In this context, the structural module can be applied to façades or roofs, where the light and flexible materials integrated into the proposed movement result in a solution that presents an independent response in order to adapt the environment and users needs, improving the functional performance of buildings.

Bringing to the structure development principles of biomimicry, science area that seeks to bring functions and behaviors found in nature and to incorporate in the architecture field, the structure concept is based on the leaves of trees or plants. The leaves present a diversity of shapes, colors and dimensions, being able at certain times of the year present changes, as shape, color and size. This ability to change through seasonal variations initially brings the concept of change to the structure design. From this, it followed a simple and structurally balanced spatial/formal configuration presenting, therefore, a triangular three-dimensional shape rereading the anatomical elements behavior of a leaf (Fig. 1).

Another important point of the leaves is the ability to resist – even presenting a thin surface – and to adapt/deform due to the forces, such as wind and rain, through their flexible anatomy, bringing the adaptability concept to the structure. Thus, the elements 1 and 2 (midrib and blade edge) must corresponding to bending-active elements; the 3 corresponding to the blade is represented in the structure with the use of architectural membrane (textile structure) and the 4 are the surface elements (vein) that in the structure must have rigid behavior, since the veins represent the leaf skeleton, giving structure and resistance to the blade.

In general, the idea of the leaf for the module refers to concepts of change, movement, flexibility and adaptation, bringing a rereading of the form and mechanical behavior of an element found in nature to the reality of architecture and engineering. Additionally, the leaves may also bring other inspirations of incorporation into the structure, not only spatially and mechanically, but also at the functional level. Concepts such as self-cleaning, as can be seen in the ability to repel water from some leaves, or even color change during the year, may be important features found in leaves and that can be applied to the structure, more specifically to the membrane, through of innovative polymers that are capable of reproducing such capacities.

Defined the general shape of the structure, three physical models were developed, from which were taken important notes for the final definition of all the elements that compose the structure, and a final model was developed (Fig. 2). Using a composite material with carbon and glass fibers, and fabric with small elasticity, the model served to analyze the performance of the proposed structural set and, mainly, the behavior of the fabric according to the transformations and movements that the structure is subject. The movement in the model was generated by means of strands fixed in the connections of the triangle base, in order

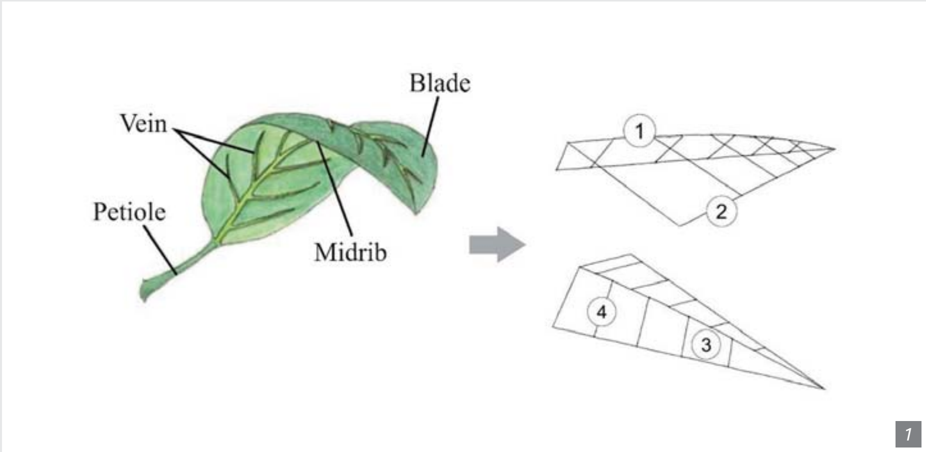


Figure 1. Concept of the formal design based on the anatomy of a leaf.

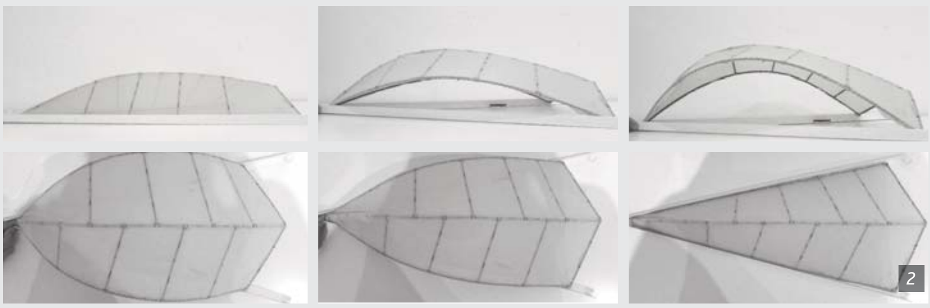


Figure 2. Photos of the physical model – top and lateral views.

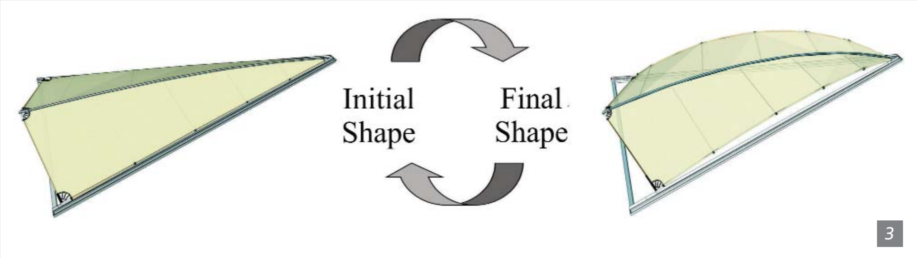


Figure 3. Structure reversibility.

to simulate the force mechanisms application for the structure transformation.

With this model it was possible to conclude that the structure works integrally, with the membrane remaining in tension during the movement and that depending on the elasticity modulus of the material used for the bending-active elements, it is possible to obtain a great transformation with little displacement and applied force on the connections.
The materials for composing the developed structure should follow parameters such as flexibility, strength and low self-weight, since two of the applied structural principles base their adaptability on the elastic behavior of the materials, which results in a global structure with reversible capacity (Fig. 3). This reversibility represents the formal change capacity of the structure caused by the movement mechanism that, when applying punctual forces, is able to alter and return to the initial form, corresponding to a structure with non-linear elastic behavior.

Based on these parameters for the materials definition, the use of fiber reinforced composites materials presents a constructive alternative of great efficiency when it is intended to have a good relation between mechanical properties and low weight. In addition, since the module represents an adaptive structural solution aiming the user ambient comfort, reducing the energy consumption of buildings, materials that present intrinsic characteristics durability, reduction of overall cost according to the life cycle, low power consumption for manufacturing and low weight for transportation, and assembly should be prioritized.
The definition of the membrane to be used is also a very important point for the structure. The membranes can present different compositions in face of service needs, as the most usual for structural design of PVC/polyester, PTFE/glass fiber or even the ETFE film. Usually, for the movable membrane structures design – such as folding and unfolding – PVC/polyester composite membrane are adopted. However, in the case of the studied module that presents a shape changes through the bending-active elements, the behavior of the membrane in relation to the global structure must always be tractioned to resist the external forces. In this context, the structure allows the adoption of all the membrane compositions and the definition of the type of membrane to be used is dependent on the functional needs or aesthetic issues.
Due to advances in nanotechnology, biotechnology and electronics, that investigate the materials properties and develop methods to alter and produce dynamic behaviors capable of providing the materiality of an interactive operation that can read and adapt to different surrounding conditions[10] the use of membranes allows architects and engineers greater freedom of creation, being able to think beyond their mechanical properties. Among the new functional and aesthetic capabilities is the ability to self-clean, change color and appearance in response to external influences or the ability to produce light through the use of chromic and luminescent polymers, or even photovoltaic capacity through the use of organic solar cells on the membrane surface.

Application study

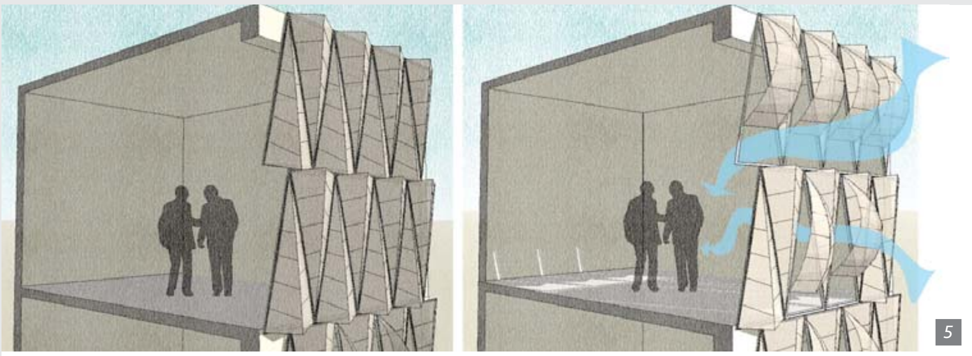
The design of the module is intended to integrate adaptive structural principles in order to create a structure that can be applied in new or existing buildings, or other appropriate situations, that the shape changes and adaptability are capable of functionally efficient architectural solution. As main application possibility the use in roofs or façades is highlighted.

In order to exemplify this context, it was necessary to bring an application case with considerable relevance, so that the proposition would benefit a real problem. Thus, it was proposed to apply the structure in an existing situation, designing a cover for the *Paço dos Duques de Bragança* central courtyard. *The Paço dos Duques de Bragança* (Figure 4) is one of the most important buildings located in Portugal mainly about the history of the country. A medieval civil architecture example with peculiar characteristics in the Portuguese territory[11], the gothic language building dates from 1420 and it is organized in a quadrilateral layout, presenting a rectangular design as a central courtyard with the cloister that surrounds it. Currently, the building is used as one of the most visited museums in Portugal.

The incorporation of the module for this composition seeks to present an adaptive architectural and structural solution capable of protecting the central/internal courtyard space of the building of climatic variations, making it possible to use this space for new uses and for different purposes. Therefore the concept of a general kinetic structure is considered, with the capacity to change the shape, adapting to the users needs and the environment, where the proposition of the global structure followed some design guidelines:

- The general structure should be independent with no fixation and support in the building structure, following concepts of maximum conservation and respect for the constructive system of the monument with high patrimonial value;
- It must respect all the architectural elements existing in the courtyard, important parts for building identification and characterization;
- Distinguish between the building and the new structure;
- Facility of assembly and disassembly also bringing as principle the reversibility of the structure, being able to be removed without leaving permanent intervention traces;

Figure 4. Superior view and courtyard of the Paço dos Duques de Bragança building in Guimarães, Portugal.



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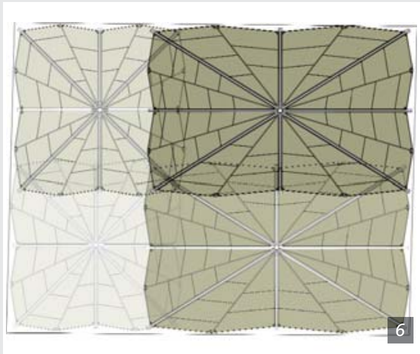

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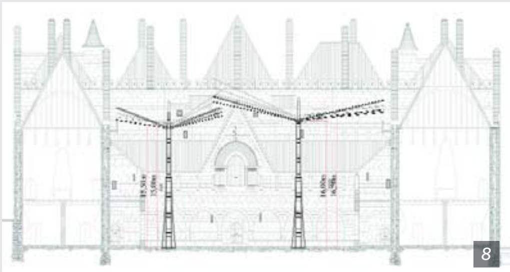

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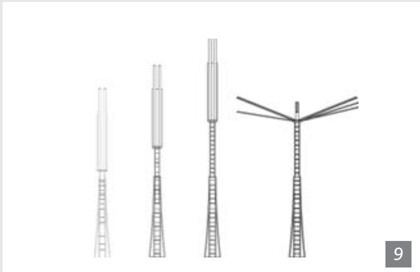

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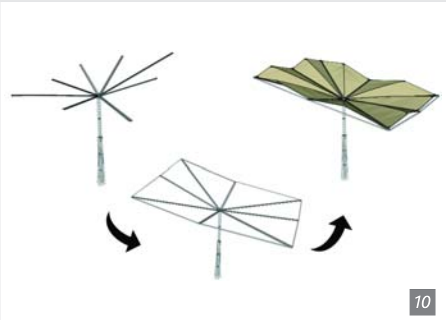

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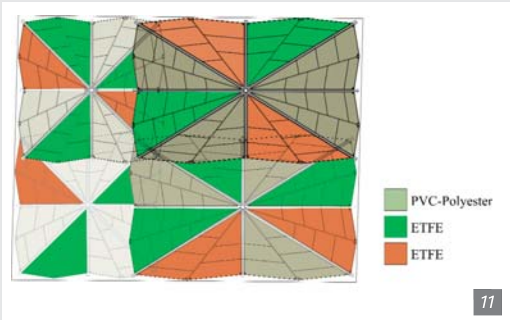

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Figure 5. Structure concept based on a palm tree used for Façade application.
Figure 6. Top view of the cover composed by four independent structures.
Figure 7. The global structure based on a palm with eight modules.
Figure 8. Section demonstrating the height of the structures in relation with the building.
Figure 9. The global structure movement.
Figure 10. Assembly of the global structure.
Figure 11. The different membrane compositions of the modules applied to the cover.

- Ability to adapt to the environmental through the incorporation of the developed module, allowing the natural lighting and ventilation in the space with the shape and material changes.

Joining the concept for the development of the module based on the leaves with the parameters highlighted in the guidelines, the structure design to the courtyard cover started from the general idea of a palm tree (Fig. 5).

The palm is a plant that reaches in some species high heights, presenting the leaves only in the highest part, forming a tuff at the stem high end. Starting from the same conceptual origin of the module based on nature, it was found relevant to use a tree or plant to conceptualize the cover design, incorporating several studied modules that correspond to the leaves. Another point about the palm is that with only one support that corresponds to the stem it can have a large diameter treetop without the need for other ways of support to resist the external actions, bringing the concept of structural independence. Therefore, the cover proposal is composed by four structures that refer to four palms (Fig. 6).

In a square/rectangular composition, the structure is formed by eight base rectangle-triangle modules (Fig. 7). Basically, it is composed of the support column, the rigid bases and the light upper module structure. The column is a mobile lattice structure presenting an organic shape in the base with curved elements that resembles the stem shape, resulting in a larger area of base, and each structure presents a height difference due to their overlap.

The 'arms' inclination, in addition to the function of enabling the structure to conform to the building architectural elements, directs the rainwater to the falling pipe which is located in the structure center (Fig. 8). To facilitate the assembly of the structures, the proposition of the columns and the mechanized arms, resulting in a kinetic structure, enables the rigid structure to be positioned at the intended height independently. On a circular base with eight spaces where the arms are fixed with a rotating mechanism, the rigid bases initially positioned vertically take the final position when their final height has already been reached, beginning the opening in order of the structure from lower height to the higher height (Fig. 9).

After the rigid structures have been opened, there is the application of the locking between the arms for a greater structure resistance and also the upper light structure application already mounted, because their low weight makes easy to handle, fixing the three points of support (Fig. 10). Once assembled, each module will have independent operation through the endless motor mechanism able to change the shape through the active movement and the bending of the elements, allowing openings for the natural ventilation and ilumination of the space.

The kinetic modules composed of bending-active elements with architectural membrane for their closure should present different behaviors regarding the functional and mainly aesthetic aspects in the covering structure. The idea is bringing to cover – besides new concepts of architecture and engineering – a structure capable of interacting with the environmental and users, so that the incorporation of innovative materials present in addition to the functional parameters, a differentiated aesthetic becoming a featured element in the building (Fig. 11).

Essentially, the nude color modules are composed of semi-translucent PVC-Polyester membranes with organic solar cells to give photovoltaic capacity to the module, generating energy feeds to the led illumination present in the rigid arms of the structure. This semi-translucency allows users to see important building elements and diffuse natural light, but at the same time prevent the direct sunlight, obtaining better space comfort.

The green and orange/brown modules are composed of ETFE film, completely transparent with thermochromics polymers that, receiving the direct sunlight and the thermal energy gain, alter their color by changing the appearance and becoming more opaque to block the entrance of direct solar rays. These thermochromics modules must also contain luminescent nanomaterials enabling the film to emit light for a period of time after a thermal energy gain. Therefore, the thermal energy gain through the solar rays enables the module to change the color instantly during the day and allows to emit light during the night.

The images correspond to the modules behavior simulation in the cover courtyard application. The first perspective (a) corresponds to the structure in the initial transparent appearance without the gain of thermal energy. With the onset of direct sunlight (b), the ETFE modules change to the determined colors (c), demonstrating their luminescence at night (d). The color was based on the module concept inspired by the leaves, being the green representing a leaf in the period of spring/summer with high amount of chlorophyll and the orange-brown caused in the leaves during the autumn due to the decrease in temperature and the consequent reduction of chlorophyll production.

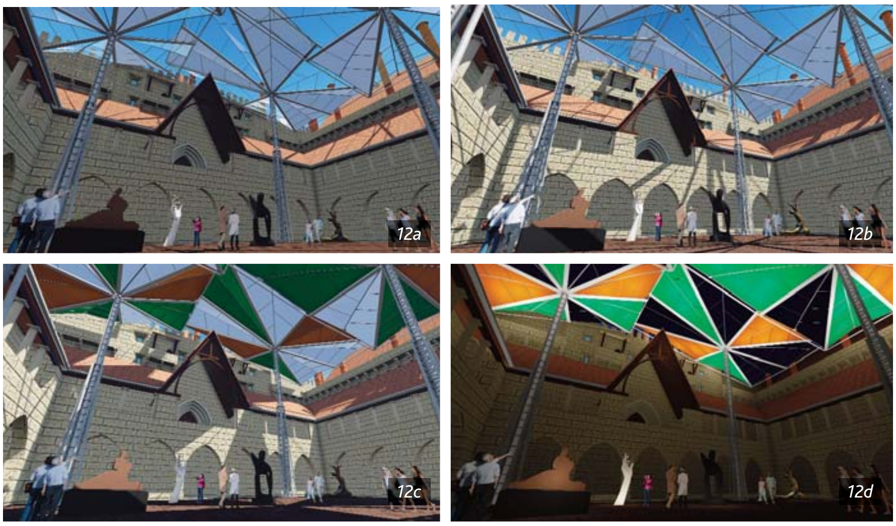

Figure 12 a-b-c-d. Module behavior simulation.

Conclusions

After studying and developing the structure through the empirical analysis of physical models, it was possible to successfully complete the objectives established at the beginning of the work. Thus, this research contributed to advance the knowledge in the area of special architectural structures, bringing something new that is the integration of three structural principles in the contemporary context as solution of functional problems in new and existing buildings, which have only been the focus of a few investigations in this scenario until today. It could be first concluded that the design of structures integrating architectural membranes with bending-active elements capable of formal alterations represents a high design complexity. It is extremely important to know the properties of the materials that compose these structures, as well as the understanding of the behaviour and the components that each structural principle encompasses, in order to find the ideal integration solution between them. In addition, it is also emphasized the need for multidisciplinary professionals from the creation phase.

Having as a conceptual inspiration an element from nature, the developed module had to refer the anatomy of the leaves of plants through the elastic capacity of the bending-active elements and the adaptable performance of the architectural membrane. However, in order to achieve that, specific connection elements had to be developed, designed for the adaptation of the general elements of the structure during the shape changes caused by the movement and in order to keep the membrane in traction at all stages. For this, the physical models in small scale were of total importance, because with them it was possible to reach the best form for the membrane to remain tensioned in all structure changes, and also prove the feasibility of creating a structure capable of integrating the concept of kinetic with architectural membrane and bending-active elements.

As a result, the development of a structure that is open for changes in dimensions and angulations was achieved, so as to be able to compose different applications. This flexibility allowed the design of a case study to be implemented as a courtyard cover of the Paço dos Duques building and could be easily applied in the real context, presenting the adaptive structures as a very efficient solution for interventions. Moreover, the application of new materials and new concepts in a context with high cultural value for the city and, consequently, for the country, aims to highlight even more the use potential of these kind of structures in the architecture field. Also, through the incorporation of certain innovative materials in the architectural membrane, it is possible to obtain innumerable potentialities in the development of this type of structure, optimizing still more the functional performance, besides an aesthetic variety that give greater freedom of creation to the professionals of the construction field.

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References

[1] Obata, S. H; Alonso, C. E. Mobilidade das arquiteturas têxteis e tensoestruturas. Paper for Exacta magazine, vol. 9, n. 1, p. 103-120. São Paulo, 2011.
[2] Brancart, S; De Laet, L; De Temmerman, N. Transformable bending-active structures: manipulating elastic deformation in kinetic and rapidly assembled structures, proceedings of the International Conference on Structures and Architecture (ICSA), Guimarães, 2016.
[3] Moreira, R. A. S. Novas possibilidades na arquitetura. Dissertation of Master in Architecture and Urbanism, University of Porto, 2013.
[4] Moreira REF. Utilização de membranas tensionadas leves na execução de estruturas especiais. 2012.
[5] Mérida KR, Fangueiro R. Arquitetura têxtil: liberdade de design, funcionalidade e sustentabilidade, 2012.
[6] Lienhard, J; Alpermann, H; Gengnagel, C; Knippers, J. Active bending, a review on structures where bending is used as a self-formation process, International Journal of Space Structure 28, p.187-196, 2013.
[7] Puystiens, S.; Craenenbroeck, M. V.; Mollaert, M.; Hemelrijck, D. V, Laet, L. Implementation of Bending-Active Elements in Kinematic Form-Active Structures: Design of a representative case study. Structural Membranes 2015: VII Internacional Conference on Textile composites and inflatable Structures. Barcelona, Spain. p. 368-378, 2015.
[8] Fox, M. A. Kinetic Architectural Systems Design in Transportable Environments 2, de Robert Kronenburg. London: Spon Press. p. 163-186, 2003.
[9] Razaz, Z. E. Sustainable vision of kinetic architecture. Artigo para o Journal of Building Appraisal, 5, 341-356, 2010.
[10] Sousa, J. P. Tectónica Digital: (Re)inventando a Materialidade. Arquitectura e Vida, p. 32-36, 2005.
[11] Brito, M. Paço dos Duques de Bragança em Guimarães: metamorfose da imagem na Época Contemporânea. Dissertação de Mestrado em Arte, Património e Restauro, Lisboa, Departamento de História, Instituto de História da Arte, Faculdade de Letras da Universidade de Lisboa, 2003.