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Membranes for functional conditioning: Report on the design and construction of two active bending structures incorporating reused materials

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ABSTRACT

This paper describes the design and assembling process of two experimental structures located in the University of Minho's School of Architecture, Art and Design, carried out between 2020 and 2022. Both were designed using the concept of active bending, assured by poles made of Glass Fibre Reinforced Polymer (GFRP) as supporting elements to membrane mesh made in PVC coated polyester. The assembling process allowed participants to experiment all the steps related with the design and construction of membrane structures with active bending elements, considering their advantages and disadvantages. The ability of membrane structures for the functional conditioning of the built environment was explored in two different scenarios, showing that they can be adequate both in outdoor as in indoor contexts. The idea of learning by doing served as the foundation for the pedagogical practices used. Each practice was discussed and tailored to the specific situation, regarding the conditions of the site, the participants involved and the functional conditioning requirements of each space.

1. Introduction

This paper presents the concept of using membranes for functional conditioning systems, showing examples from previous works developed by the author and reports the design, testing and construction of two membrane structures, that were built in the University of Minho's School of Architecture, Art and Design, located in Azurém campus, in Guimarães, and had students participating in its conception and construction. Membrane structures have experienced a large evolution over the last 50 years, especially with the contributes of Frei Otto and Horst Berger. Membranes can be connected with sustainable strategies in architecture enabling versatility through simple form and usage adaptability, dry assembly and disassembly, reusability and recycling, durability, as well as affordable construction and transport. They are also responsible for architectural designs that are luminous and ephemeral, which increase practical benefits and promote unconventional design approaches not typically connected with common construction materials [1]. Membrane structures can be explored for functional conditioning, acting as thermal regulators for solar passive heating and cooling exterior [2] and interior spaces [3], controlling natural and artificial lighting by acting as lighting diffusers, but are also able to improve acoustic performance due to their properties to act as diffusers or absorbers, depending on the type of membrane applied and its geometry [4]. Bioclimatic strategies, which often aim to reduce or even eliminate energy usage while preserving indoor comfort, while responding to the local climate and being respectful of the ecosystems [5,6]. These strategies may involve the utilization of a variety of resources, such as the proper orientation of windows to optimize passive solar gains, the use of shading devices, promote ventilation or evaporative cooling [7]. In addition to the aforementioned bioclimatic measures, a building that pretends to be eco-efficient should also optimize other aspects during its life cycle. Membrane buildings utilize very little energy for the extraction, production, and transportation of raw materials (embodied energy), as well as in the transportation and assembling of finished goods. [4]. Using as little material as feasible is almost always advantageous from the standpoint of material resources [7], not just when using new materials, but also when reusing and even recycling, as the transport costs are significantly decreased in all the life cycle scenarios considered. New ways for design exploration and evaluation are now available

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thanks to advanced computational tools and techniques. Performance-based design has an edge over conventional design approaches since it incorporates simulations and environmental studies in the early design phase. Digital fabrication methods make it simple and affordable to create tangible prototypes that may be used to test constructability, material behavior, and aesthetic attributes to choose the best design solutions. Such technological applications encourage ongoing development of the architectural sector and enhance the bonds between design and craftsmanship. Universities and construction firms promote these cutting-edge trends in design and research. The goal of the university is to produce, transfer, and use knowledge through research and in response to societal demands. Universities continue to be the best environment for the creation and testing of novel ideas. The fundamental reason for this is that academic projects are typically utopian in nature because they are not intended to be realized or have a specific client, and as a result, they do not face the same financial, legal, or even cultural constraints as actual projects do [1].

However, this paper reports experimental work carried out in academic context based on the contact with real scale construction, a teaching approach based on "learning by doing" [8].

This was possible due to the fact that membrane structures are composed of dry joint system where all the materials used on real scale can be reduced to models that are able to accurately replicate it in reduced scale, as reported in several publications by the author [1,2,11].

2. Functional conditioning structures in the University of Minho's School of Architecture, Art and Design

The potentialities of using membranes as functional conditioning structures are being researched since 1995 in the University of Minho. In a MSc thesis developed by the author in the Textile Engineering Department [9], concluded in 1997, was tested the effect of using black Chromotropic Pigments printed over white textile membranes in the envelope of buildings in order to reduce their thermal heating needs.

A test cell was created in 2010 to investigate the environmental and structural potentials of low span membranes on a site located in the north side of the Architecture School building in the University of Minho's Azurém Campus in Guimarães. This prototype building had a cubic form of 2,5x2,5x2,5m (Fig. 1). The cube edges are composed by a structural frame made of aluminium profiles that support membrane in all the cube faces. The west and east façades were made of an opaque white polyester/PVC membrane of 2,5 × 2,5 m fixed to the aluminium profiles by a PVC rod. These membranes were tensioned by four poles of stainless steel with 20 cm long pressing against the membrane by two crossed steel cables fixed to the corners, that also assure the cross stabilization of the structure. Several functional conditioning systems of membrane buildings were tested in this prototype under supervision of the author, such as the Folder Wall System Façade in Alex Davico PhD thesis [10] (Fig. 1a) the shading and optimization of thermal mass in a MsC thesis by António Reis (Fig. 1b) [11] or a pneumatic transparent PVC façade that allows to change the visible light transmission in an active way by changing the position of an intermediate layer located inside an air cushion, developed by Integrated Master students in the Curricular Unit Lightweight Constructions (Fig. 1c).

2.1. Interior structure for functional conditioning of a drawing room

Since 2009 the "Lightweight Constructions" Curricular Unit of the University of Minho's Integrated Master's degree in Architecture, has acted as a trial ground for creative construction techniques that are low-cost, low-tech, and sustainable using lightweight construction technologies, where membranes have a significant role both in structural as in functional aspects. The defeats launched by the author to students within this curricular unit have always been related with the Architecture School building or to its close vicinity and were focused to solve real life problems. During the academic year of 2009/2010 the challenge was to design and implement facades in the Membrane Test Cell previously referred, a group of students proposed a pneumatic transparent façade system (Fig. 1c), that was produced and installed. In 2015/2016 the defeat was to design a structure for an interior Stage Cover with Membrane Structure for the Drawing Room of the School of Architecture Building in the Azurém Campus of the University of Minho. This room has a cubic shape of approximately 10x10x10m. This shape gives the room an impressive sensation of large space wideness, however its high ceiling height is responsible for significant acoustic, thermal and luminous discomfort problems. Regarding the acoustics, the reverberation is significantly high and not appropriate for a class room. In what respects the thermal issues, as this is a drawing room, there are live model classes and no air conditioning (only radiators located in the side walls but on a higher level), so, apart from the low energy efficiency associated with the necessary use of convectors that are used pointing directly to the models, a significant discomfort is still felt in winter, as the hot air is quickly escaping to the higher level of the room. In summer, the high clerestory windows located in the roof are not operable, so it is also not possible to evacuate the hot air accumulated in the room. The control of natural lighting is also complex in this room, as the roof windows don't have any shutters. This gives a uniform lighting during day, that in drawing can be problematic, when there is the need to accentuate the shading effects with side lighting. Given this defeat to the students, several proposals were developed. Some examples of the studentś proposals are shown on Fig. 2.

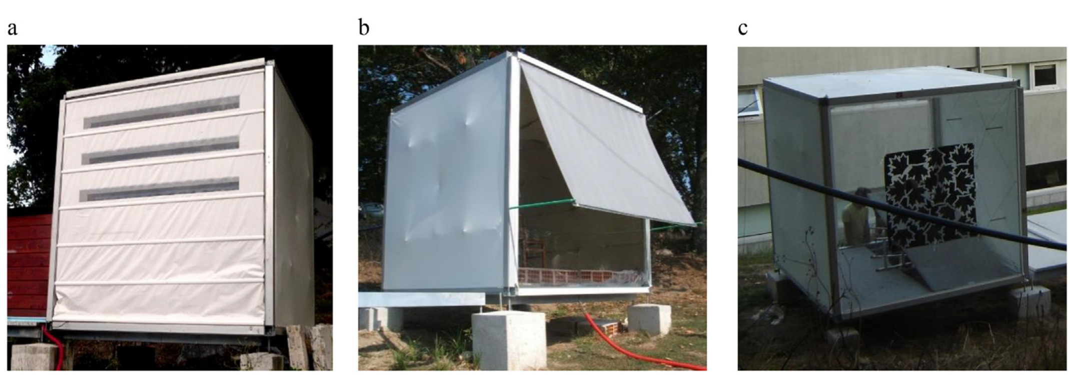

Fig. 1. (a) Folder Wall System Façade; (b) Testing the effect of Thermal mass; (c) Pneumatic transparent Façade (students Alvaro Silva and Diogo Rodrigues).

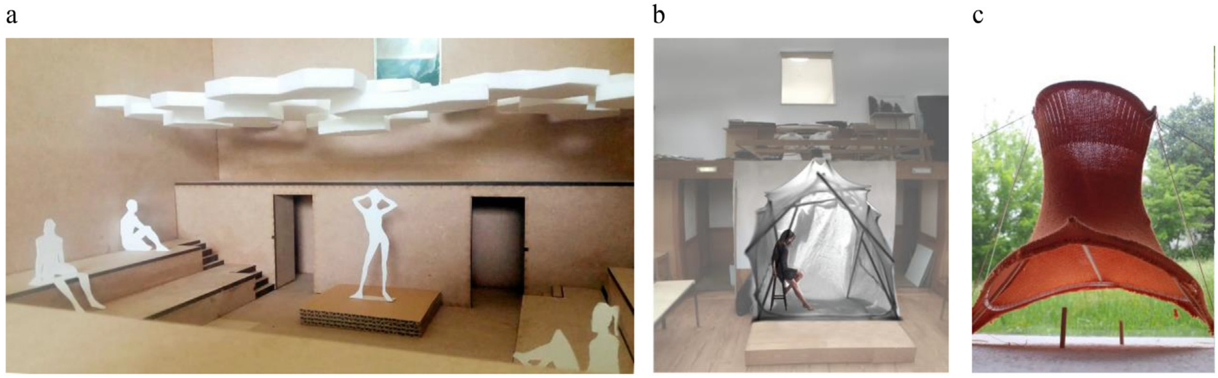

Fig. 2. Proposals from students to the Interior Structure for functional conditioning of the School of Architecture drawing room: (a) Ana Rita Terroso, Carlos Lima, Cláudia Alves and Eduarda Rocha; (b) Sara del Rio; (c) Bruno Silva.

After an internal competition, the selected design was the one shown on Fig. 2c and Fig. 3a, proposed by the student Bruno Silva. The advantage of this design was that it could be erected from the ground with no need of significant scaffolding inside the room. To allow this, the side bars should handle the membrane and upper ring weight. The membrane weight around 25 kg. The upper steel ring, the fan and the steel auxiliary parts, cables and accessories weight around 120 kg. This design was functionally improved by the author, introducing a fan attached to the upper ring (with a diameter of 3 m), destined to force the hot air down during winter and also to increase the convection sensation in summer; and an opaque horizontal retractable roller awning attached to the lower ring (with a diameter of 7 m) to control reverberation time, restrain thermal losses and block direct light. One of the main problems regarding the construction of this structure was related with the support of the upper ring and membrane. These supporting elements should be curved and attached to the lower ring, and have around 6 m in length. To decide on the most appropriate material to accomplish this task, several materials were tested to compression bending, such as spring steel bars and tubes, pultruded (GFRP) bars and tubes, and bamboo canes (Fig. 3b).

The spring steel bars had the problem of a higher weight and no availability in the required sections. The bamboo was an interesting option, with a very high compression resistance, but local bamboo tested had problems with curvature, they could not be curved in active bending, or if forced to curve they broke. The material chosen in terms of its lower cost and weight, as well as availability and active bending ability, was the GFRP rods, that presented good results in low sections and in simulations. This study was produced by José Torcato under supervision of Miguel Azenha. However, both specially produced 20 mm section rods and commercially available GFRP tubes of 40 mm section broke on tests. However, when subject to curvature with active bending compression tests, it suffered from short term fatigue and broke, as the available pultruded tubes were not produced to be curved. The selected option was finally to apply reused pole vault poles. The ones used, with a length of 6 m, were designed to support the weight of a 80 kg athlete and were also able to resist to the medium term fatigue tests carried out (Fig. 3c). Apart from structural validation and testing delays, budgetary and bureaucratic restrictions, aggravated by the pandemic crisis, the construction only started in 2021 and was completed in 2022. The assembling process is shown on Fig. 4-a-e. Fig. 4f shows the final result.

2.2. Exterior structure for protecting rammed earth benches

During the academic year of 2020/2021, with partial support from the University of Minho rectory (IDEIA - Support Program to Innovation and Development of Teaching and Learning Projects), a workshop named as "Hands on Work" was promoted. During this workshop, students of the Curricular Unit "Sustainable Materials" under supervision of Rute Eires, designed benches using different techniques of Earth construction. After an internal competition, the chosen solution was a rammed earth bench design. In order to protect this bench from rain and to assure shading in summer to the bench users, the author designed a

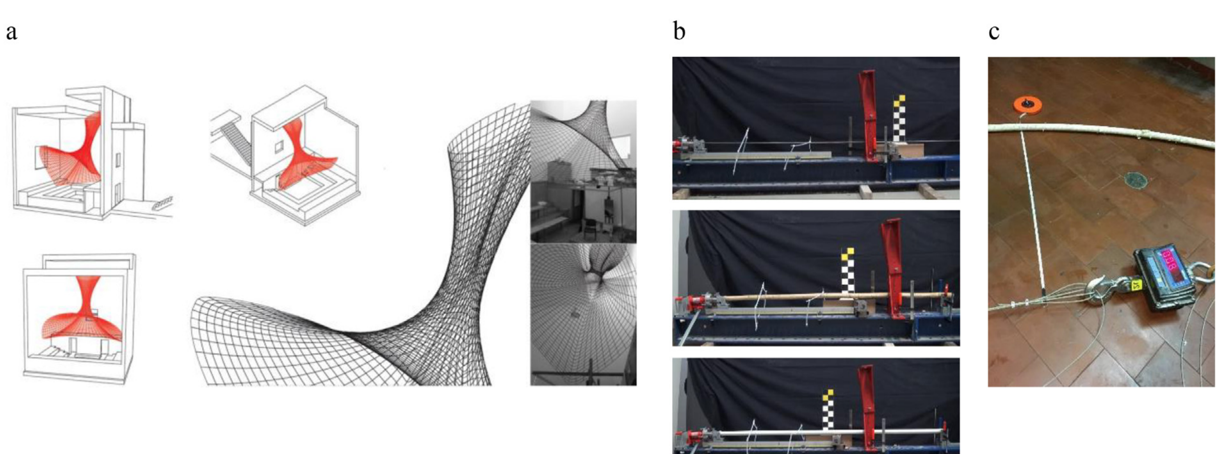

Fig. 3. (a) Selected Proposal from student Bruno Silva (drawings by João Pedro Silva) Compression bending tests: (b) in laboratory; (c) in field.

Fig. 4. (a-e) Assembling of the Drawing room functional conditioning structure (f) Interior Structure final result.

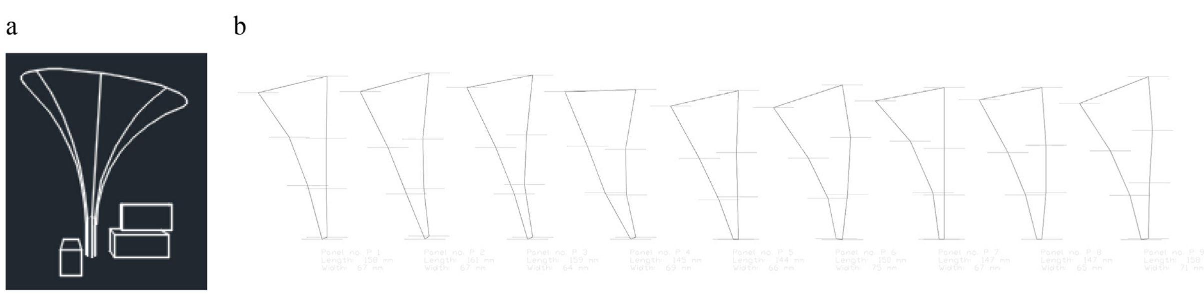

Fig. 5. Exterior membrane structure: (a) Schematic design of the structure and benches; (b) cutting pattern of the exterior structure membrane.

membrane structure (Fig. 5a). The design was based in remnant materials from the tests and construction of the Drawing room interior structure presented in the previous section, namely GFRP bars for the supporting structure and the non-used membrane resulting from the cutting pattern optimization on the Interior Structure, that allow some saving in the used membrane material. Fig. 5b shows the cutting patterns of the Exterior Structure, divided in 9 parts. The support elements were initially 3, but during the assembling tests it was concluded that 3 poles were not enough to support the lateral winds, even if they could support the weight of the membrane. In the final solution 9 supporting vertical poles were inserted in the connections between all the membrane panels shown in Fig. 5b. The upper arch was also resultant from bending 3 poles, so in total 12 GFRP rods were applied in the structure. The connectors between the rods were specially designed and produced in massive aluminium. The base structure is made in Corten steel and foundation is assured by connecting the base structure to the benches. The membrane was sewn in the Textile Engineering Department (Fig. 6a and b). The structure was tested (Fig. 6c and d) and assembled by 4th year Integrated Master in Architecture Students, a PhD student in Architecture (Lujain Hadba) and 5th year Civil Engineering students as an extracurricular activity. The final result is shown in Fig. 7.

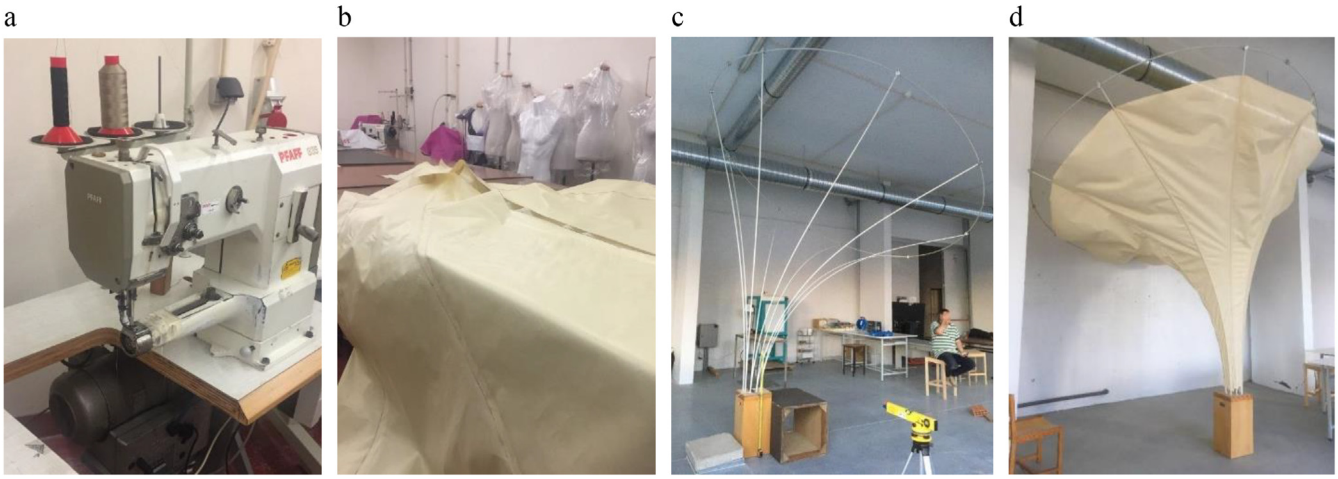

Fig. 6. Exterior membrane structure: (a) Sewing machine in the Textile Engineering department; (b) membrane being sewn; (c) structure assembling test; (d) membrane assembling test.

Fig. 7. Exterior structure final result.

3. Analysis

The Interior and Exterior functional conditioning membrane structures presented in this paper involved students but also professionals (steel work in both structures, sewing of membrane and scaffolding works in the interior structure). The ability to enable functional optimization of the existing buildings is shared by both of the structures presented, new buildings and exterior spaces in a low cost and environmentally sustainable manner. Table 1 synthetizes the major aspects considered in the design and construction of the two structures presented in this paper.

Table 1
Analysis of the structures presented.

	Interior Structure	Exterior Structure
Functional parameters considered	Acoustic, thermal and natural lighting control	Protection from rain and solar radiation in summer.
Design	Bruno Silva and author	Author
Construction	Students, author and Professionals	Students
Membrane material	PVC coated polyester mesh	PVC coated polyester mesh (reused)
Supporting materials	Reused Pole Vault poles (GFRP)	Reused GFRP rods
Connectors and accessories	Steel connectors, stainless steel cables and fasteners	Aluminimum connectors and stainless steel cables (reused)

4. Conclusions

The structures presented in this work are the outcome of a similar approach that included: functional conditioning of built environment, minimum use of materials, maximum reuse of existing materials, involve students in its design and/or construction. In a preliminary stage, the author supplied students with the underlying structural and functional concepts that guide the construction of membrane structures. In a second phase, following examination of the built environment in the area and collection of the available materials, participants together with the author proposed a design for a membrane structure. In a third stage the construction and assembling was carried out with students whenever possible. The interior structure, due to the large dimensions and unpredictable behavior of the active bending poles, presented some problems during the construction, that obliged to use some specialized labor in the steel work and during assembling process, but the exterior structure, due to its reduced size and the experience acquired on the assembling of the first structure, allowed to use only non-specialized labor and the university laboratories for all the construction and assembling process. This broadened the students' awareness of these kinds of structures, suggesting a different paradigm from how they are typically thought and designed. They were able to participate in all the stages of a membrane structure for functional conditioning design, from conception to production, testing and assembling in real scale. It is expected that the experience gathered with these experimental structures will lead to future developments in the field of functional conditioning of the built environment using membrane structures.

CRediT authorship contribution statement

Paulo Mendonça: Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] P. Mendonça, M. Macieira, Architectural Membranes for improving the functional performance of buildings in SMC Magazine n.3/2019 Membrane Materials for Sustainable Architecture; SMC Association, Naples, Italy, ISSN: 2420-8213 Retrieved October 6th 2022 from http://www.sustainablemediterraneanconstruction.eu/SMC/Special03.html.

[2] L. Hadba, P. Mendonça, L. Silva, Functional Conditioning Systems for Urban Environments - Regarding Hygrothermal Comfort, Air and Noise Pollution; in Sustainable technologies for the enhancement of the natural landscape and of the built environment; Ed: De Joanna, P.; Passaro, A.; 2019, p. 385-416.

[3] T. Devulder, The thermal response of textile membrane constructions, University of Nottingham, United Kingdom, 2005 (PhD Thesis).

[4] J. Knippers, J. Cremers, M. Gabler, J. Lienhard, Construction manual for polymers + membranes, Institut für internationale ArchitekturDokumentation, Detail/Birkhäuser, Munique/ New York, 2011.

[5] Givoni, Baruch; "Climate considerations in Building and Urban design;Van Nostrand Reinhold; 1998.

[6] D. Lloyd Jones, Architecture and the Environment: Bioclimatic Building Design, Laurence King Publishing, London, 1998.

[7] Mendonça, P. Living under a second skin – Strategies for Reducing the Environmental Impact of Passive Solar Buildings in Temperate Climates; PhD Thesis in Civil Engineering, University of Minho, Guimarães, Portugal, 2005.

[8] S. Winn, Learning by doing: Teaching research methods through student participation in a commissioned research project, Stud. Higher Edu. 20 (2) (1995) 203–214, https://doi.org/10.1080/03075079512331381703.

[9] Mendonça, P. Smart Applications of Textiles in Architecture. Design and Marketing MSc Thesis. Textile Engineering Department, University of Minho School of Engineering, 1997 (in portuguese).

[10] A.F. Davico, Evaluation of housing spaces: Influence of partitions and furniture, PhD thesis in architecture, University of Minho, Guimarães, Portugal, 2013 (in portuguese).

[11] A. Reis, Functional and economic assessment of light constructive solutions, MSc thesis in civil engineering, University of Minho, Guimarães, Portugal, 2010 (in Portuguese).