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## CONTENTS

# TEXTILE MEMBRANE DESIGN: CASE STUDY OF A MEMBRANE HOUSE PROTOTYPE IN PORTUGAL

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***Abstract:*** The increasing speed in which technology is developing, as well as the social and economical changes are quickly turning buildings constructive systems and building design methodologies obsolete. The research on faster, cheaper and environmentally more respectfull building technologies are growing concerns in buildings design. These are some of the advantages of textile membranes. In a few millimetres membrane we have a self-supporting material, a sunlight filter capable of absorbing or reflecting the ultraviolet or infrared ligh and an isolating material for thermic or acoustic purposes. But there is some problems regarding such structures: the complexity of the calculations needed in such a minimalist engineering, regarding its structural design, the visualisation of its forms - sometimes complex geometries, and the optimization of its functional performance - limited but also potentiated by its lightness and ephemerality. Computer-aided design has allowed designers of textile membrane structures to calculate its loads and determine their effect on projects quickly and more precisely, exploring various alternatives and options, turning the process not only cheaper, but also exploring new possibilities on the use of more efficient structures. There are also a significant number of softwares avilable that allow the functional performance evaluation of buildings, and that can also be used to evaluate textile membrane solutions with advantages related with easy and quick prediction of the building thermal performance during its service life. The apparently simple final result is normally the product of a very complex multi-criteria optimization process, from the membranes selection, the building design and calculation and the constructive systems adopted.

***Key words:*** Textile membranes, design, modular house, form finding.

## 1. INTRODUCTION

After the energetic crisis of the seventies and specially with the more recent episodes of economic crisis in the developed world, we assist that the weight per square meter of building construction is tendencially decreasing, thanks not only to a technological evolution that allows it (we have insulation and mechanical resistance capacities that are equivalent and even better than traditional thicker and heavier walls, beams and covers), but also associated with the necessity of sparing resources. We are now regarding the growing importance of the self-adjustable, self-cleaning (such as the Teflon), flexible materials and even materials that are capable to change their form (such as the shape-memory alloys) or their appearance and translucity (such as the reactive membranes and glasses). We are now making intelligent buildings - the Domotics are now a common issue. We expect in a short time the self constructive building systems, or buildings that can behave like living beings, that can breathe, that can adapt themselves to different atmospheric conditions or that can even self-repair in case of damages. Also the methodologies of project are in constant evolution, with the digital design technologies opening new paradigms on architectural and engineering thinking.

## 2. THE TEXTILE MEMBRANES DESIGN

There is a new architectural tendency spreading that bets on the introduction of more efficient structures, lighter and technologically advanced. One of its more representative materials is the textile membrane, a technical textile material with a growing market. Due to their reduced weight and tensile resistance properties, a few millimetres membrane can be a self-supporting material suitable for covering big spans, a sunlight filter capable of absorbing or reflecting the ultraviolet or infrared light and protect from the rain and moisture.

### 2.1. Deciding the surface geometry

The practical way of making a thin, flexible membrane sufficiently stiff and flutter-proof to function as a tensioned facade, roof or canopy is by a combination of curvature and pre-stressing. The deliberately induced curvature enables the membrane to transmit lateral loads which it could not do when flat. With the introduction of prestress, the membrane structure gains tensional stability, providing stress throughout the all surface and allowing it to achieve resistance to compression and bending forces as wind buffeting or uplift, that otherwise would deform and even tearing the membrane. The pre-stress must be high enough (usually half a tonne per metre width of fabric), and never be reduced to zero by opposite external forces. The sequence of diagrams in figure 1 illustrates the tensioned membrane structure static principle. As we can see in figure 1(a), if a point P is restrained by tension members anchored at A and B, that point will obviously be held stable against upward forces but will be unable to resist downward forces. Conversely, a point P that is restrained by tension members anchored at C and D will be held stable against downward forces but not upward ones, as it can be seen on figure 1 (b). And a point that is restrained by two opposed directions APB and CPD will be stable against forces from all directions, as scheme 1(c) shows. The hyperbolic curvature characterizes most of tensioned membrane geometries, the typical form is known as “sail” or “saddle” – figure 1(d).

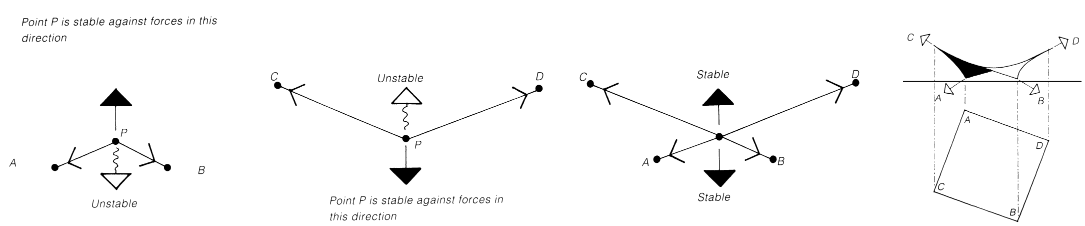



**Figure 1:** Diagram of tensioned membrane structure static principles: unstable (a); unstable (b); stable (c, d) [1].

If a flexible membrane is simultaneously curved in two opposite directions A-B and C-D, as shown in figure 1(c) and held in that shape by the application of pre-stress, then each individual point on its surface represents the condition shown in figure 1(d) and gets stable against all external forces. This simple principle is the key to understand even the most complex tensioned membrane forms.

The form of a tensioned membrane flows directly from the geometry of the boundary from which it is stretched. The boundary must be continuous.

The support and restraining on a tensioned membrane structure is done by masts, cables, lintels, arches, ring beams, trusses, anchorages, and even existing conventional heavy structures. Manipulating these elements lends to different design possibilities. Functional analysis (appearance, use, force transmission, interior conditioning) and form-finding are interdependent, so the process should be done simultaneously. Form-finding process involves a physical or virtual model to determine general shape and a computer analytical model to provide the final geometry. The two models can be done in sequence or simultaneously.

### 2.2. Computer-aided design

Computer aided design has allowed tensile structure designers to calculate loads and determine their effect on designs quickly and more precisely and to explore various alternatives and options in their work. Computer-aided design programs for these structures require specialized knowledge of the fabrics, so most of them are proprietary software programs or done in collaboration with specific membrane producers data, that are not completely revealed. Many specialist design firms have programmes giving highly reliable and accurate fabric shapes in response to stated design parameters. Two stages are involved:

• First the computer finds a form that a 'pure' membrane would assume if stretched between the proposed boundaries with uniform tension in all directions.

• Then the physical characteristics of the proposed membrane material are fed in and these inevitably produce a slightly modified form - taking into account, for instance, whether the woven material is more stretchy along its weft than its warp.

At all stages the designer has the facility of pushing and pulling the displayed forms and changing them in all sorts of ways until a satisfactory solution is reached - testing alternative support positions; different boundary shapes; different ways of collecting the surface tensions into cables and transferring these through the structure into the ground; and different types of membrane. The display can use colours to show how highly stressed the various parts of the structure are, and whether any parts of the membrane are not in tension (which, of course, is not acceptable).

In recent years, several CAD programs, primarily from European companies, have reached the market. The programs offer varying degrees of visualization and calculating capabilities, some intended more for "predesign" shape determination before precise formfinding and structural load analysis to be done. Those who wish to take advantage of CAD's benefits to the fullest and till the construction phase, will in general still need to consult with membrane producers, when the membrane properties are not included in the software.

Computer aided design is now extremely powerful but has disadvantages. One is that the designer may achieve correct answers without necessarily having any clear understanding of its underlying physical principles. The other is that even the best computer image gives a less realistic understanding of shape than an accurate physical model. For instance, relatively flat horizontal areas may seem on a computer diagram to be sufficiently curved. A frequently used approach can be to use physical modelling for preliminary form-finding and visual form-testing, and computer analysis for precisely determining the final shape, validating it for structural stability and generating the fabric-cutting patterns. The latter must be extremely accurate, and for this the computer is very useful.

While design cannot be reduced to a strict linear process it is helpful to see the design of a tensioned membrane as the sequence of stages that can be seen at figure 2.

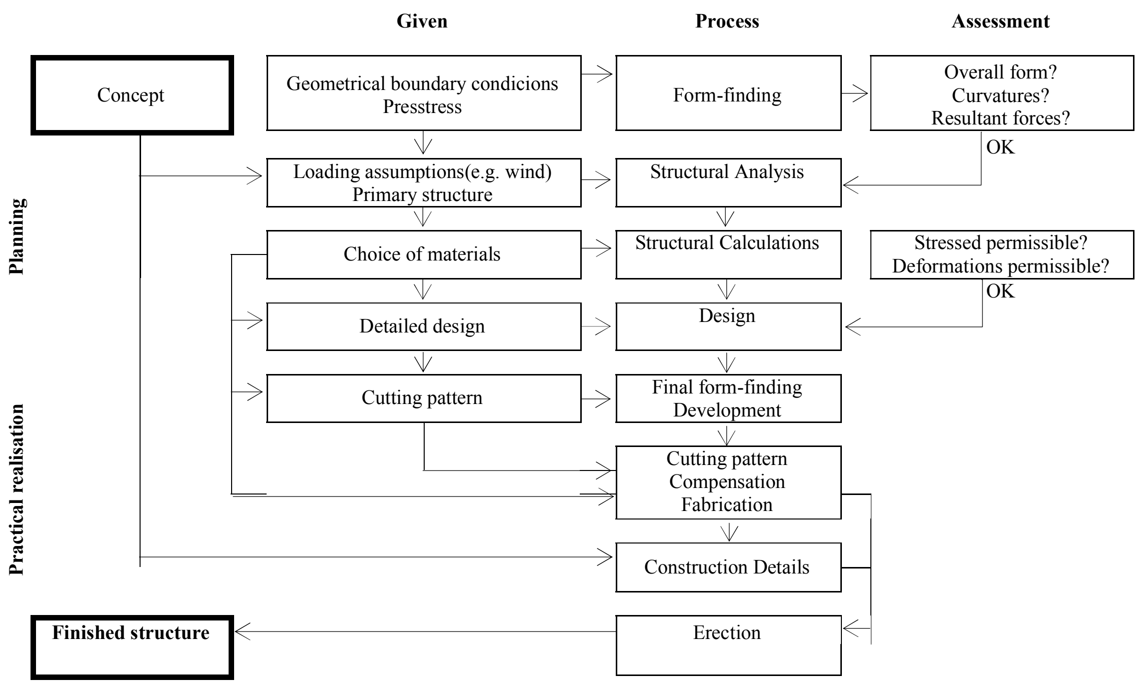



**Figure 2:** Diagram of textile membrane stages of design process (adapted from [2]).

### 2.3. Fine-tuning the theoretically-derived shape

Forms obtained by small-scale model or computer form-finding and calculated may satisfactorily resolve all structural stresses, but there may still be practical reasons for wanting to modify the shape thus established. These could include:

• Snow load dispersal. In cold climates a mass of snow may slide down the steeper sections of a fabric canopy and settle on the flatter areas, causing a deep deflection. This deflection may then become a water-filled pond which sags even deeper as more meltwater flows in, leading ultimately to membrane tearing. For this reason horizontal flat areas should be avoided or, alternatively, drained by means of gutters inserted in the fabric.

• Rainwater dispersal. Again it should be considered whether ponding may occur on the theoretically-derived shape.

• Appearance. The theoretically-derived form may not 'look right' and repeated modification may be required, possibly using large-scale physical models, to create a right-looking profile.

• Practical problems such as jointing or pre-stressing, particularly in areas of sharp curvature and in the cutting patterns.

During all these steps and specially in the cutting patterns, the computer is very useful, because all these fine-tuning is very delicate and can easily lead to the structure failure if a minor mistake is done, specially when using less flexible materials as PTFE-coated fibreglass fabric. In the case of large canopy structures, which may be subjected to unusual stress, a full-scale model may be needed to test and verify structural behaviour.

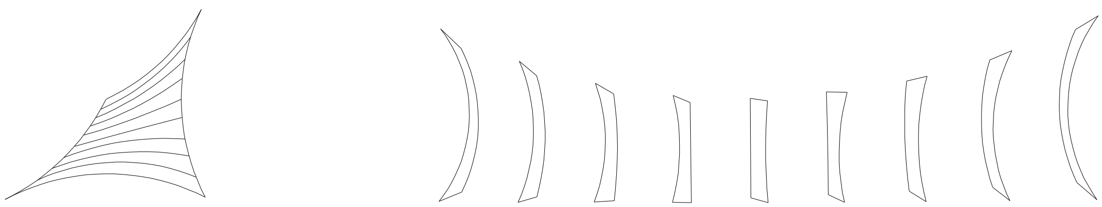
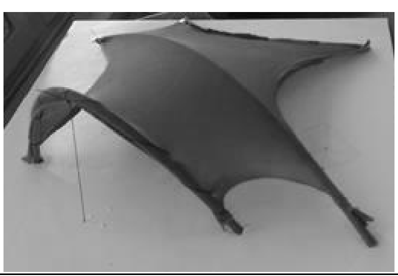
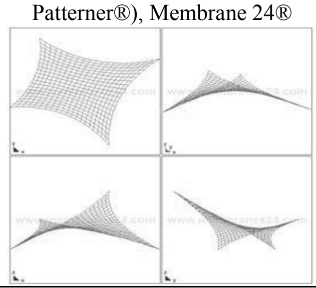
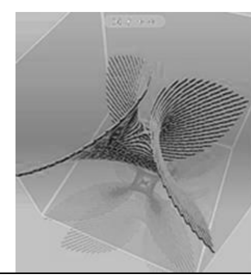


**Figure 3:** Patterning **e**xample for cutting a tensioned membrane surface by Membrane 24® software.

**Tabel 1:** Synthesis of form-finding process [3].

| **Experimental modeling** | **Infotmatic tools/ Numerical moddeling** | **Combination of experimental and numerical modeling** |
|---|---|---|
| With stretch fabrics or tensioned nets. | Form-finding, Structural design, Calculating the amount of fabric needed to define the cutting patterns and the dimensions of other structural components. (examples: MCMlite®, Tensyl-XM®, Rhino membrane®, Form Finder®, Patterner®), Membrane 24® | Create 3D digital models from series of taken photographs to experimental models, at various angles, using photogrammetry. (example: 123D catch®) |
|  |  |  |

## 3. CASE STUDY: MODULAR MEMBRANE HOUSE IN PORTUGAL

### 3.1. Lightweight means sustainable

The minimum use of materials in buildings implies a minimum overall weight of buildings and so smaller environmental impacts due to the extraction of raw materials and to their transformation processes. It also allows the reduction of energy consumption during the construction and a proportional reduction on loss factors and transport energy.

The use of membranes and polymeric foils in lightweight façade and coverings can be a sustainable option. Even if it is considered that their life span could be half of glass, their significantly lower weight per square meter makes these solutions very competitive in terms of thermal and lighting performance indicators and embodied energy, what can be seen on Table 2. An ETFE foil can weigh 40 times less than any transparent glass alternative and presents approximately 15 times less embodied energy per square meter.

**Table 2:** Relevant properties of some translucent and transparent materials.

| | Visible Light Transmission (%) | Weight ($kg/m^2$) | Embodied Energy ($kwh/m^2$) | Thermal Resistance ($m^2.°C/W$) |
|---|---|---|---|---|
| **Clear glass 6mm** | 85 | 14.40 | 73.6 | 0.16 |
| **Double glass 6(10)6mm** | 70 | 28.80 | 147.2 | 0.35 |
| **Polycarbonate clear panel (10mm)** | 83 | 2.00 | 48.4** | 0.32 |
| **PVC coated polyester** | 26 | 0.84 | 18.3** | 0.17 |
| **idem, two layers with air gap of 100mm** | 13 | 1.68 | 36.6** | 0.37 |
| **PTFE coated fiberglass** | 21 | 0.81 | 14.4** | 1.03* |
| **idem, two layers with air gap of 100mm** | 4–6 | 1.62 | 28.8** | 1.21 |
| **ETFE foil (0,2mm)** | 95 | 0.34 | 4.83 | 0.16 |
| **idem, two layers with air gap of 100mm** | n.a. | 0.64 | 9.66 | 0.35 |

*[4]
**Deduced values by the author [5] (considering just the embodied energy to make the two components of the material and excluding manufacture)

### 3.2. Membrane House Prototype

A test cell where the environmental and structural potentialities of low span membranes can be explored is built on the Azurém Campus of the University of Minho, in Guimarães. This prototype is composed by two modular cubes joint together with 2,5 x 2,5 x 2,5m (Figure 5(b)). Its main structure is made of aluminium profiles of 70x70mm, which section can be seen on Figure 4b). The west and east façades are made of an opaque white polyester/PVC membrane of 2,5 x 2,5m fixed to the aluminium profiles by a PVC rod (figure 4). Its structural stability is assured by four poles of steel with 20cm long tensioned against the membrane by two crossed steel cables fixed to the corners (Figure 5(b)), that also assure the cross stabilization of the panels. The same system was reproduced on the covering; but in this case, the steel cables are tensioned with higher stress so that covering can assure a slight slope. South and North façades are free for lightweight façade systems testing.

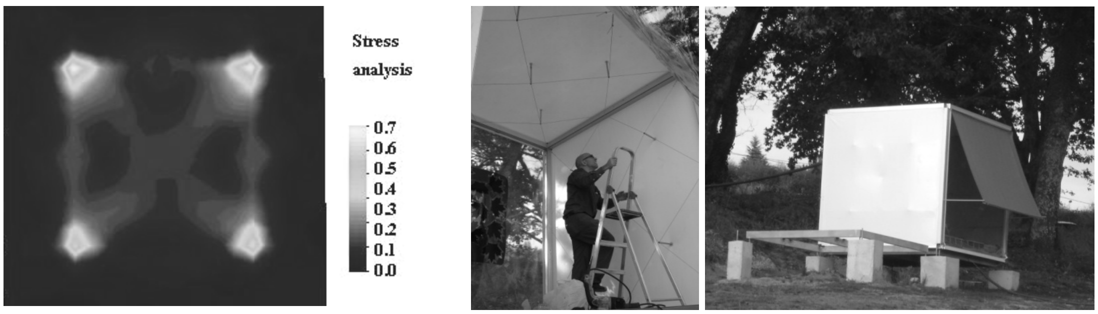
(a) (b) (c) (d)

**Figure 4**: Membrane Test cell prototype details: a) aluminium frame profiles section, b) fixing the membrane on the frame, c) fixing the steel joint connection to the frames on corners; and (d) profile corner with stretched Polyester/PVC membrane and inflatable PVC foil.

### 3.3.Structural weight optimization

The growing need to save means and resources, associated to ecological concerns, has been impelling a new minimalist aesthetic which, taken to an extreme, implies the reduction to the minimum expression of the building components. This current, called "Light-tech" [5] or also “Eco-tech” by other authors, bets on the introduction of more efficient constructive systems, especially in terms of structural performance. Most of the examples are apparently difficult to associate with sustainability, as materials used (steel, aluminum, glass) have high embodied energy and economical costs, but in many examples the structural systems used are extremely optimized in terms of the relation between weight and mechanical properties, what makes them competitive, but this is especially truth when new materials are used, such as membranes. An example can be given when comparing greenhouses from the 19th century in casted iron and glass, and a contemporary example, such as the Eden Project in Cornwall, from Architect Nicholas Grimshaw. In this project each ETFE (ethylene tetra fluoro ethylene) foil pillow weight approximately 2 - 3.5kg/m$^2$, what means less than 2% of equivalent glass cladding, while the entire pillow system including aluminum connection and steel frame support weighs between 10% and 50% of conventional glass-façade structure [7].

The prototype main structure is made of aluminium profiles of 70x70mm. The west and east façades, as well as the roof are made of an opaque white polyester/PVC membrane of 2,5 x 2,5m attached to aluminium profiles. Its structural stability (Figure 5(a)) is assured by four poles of steel with 20 cm long tensioned against the membrane by two crossed steel cables fixed to the corners (Figure 5(b)), that also assure the cross stabilization of the panels. Its detailed structural concept is described in detail in a previous publication by the author [8].




(a) (b)

**Figure 5:** Opaque membrane façade of the membrane test cell - computer stress analysis for form-finding optimization (a) [8], internal view during the assembling process exterior and view of the prototype (b).

## 4. CONCLUSIONS

A tensioned membrane building evolves a complex design process, since the selection of the membrane support structure, passing through form-finding, structural calculation and functional optimization, and finally the construction. The goal is to find the most efficient structure, considering all aspects of the design process. There are several ways to accomplish this: till a few decades ago it was only possible through physical models and manual calculation; nowadays relying almost only on computer aided design and calculation tools. There are nowadys many software tools that help on the design and fabrication of membranes structures in all the development stages. These allow calculating the amount of necessary fabric, defining the cutting patterns and the dimensions of other structural components. The programs can be more dedicated to display and form-finding, or for structural calculation, and more recently even to support automated fabrication. This paper shows the concepts behind the design of a modular housing prototype, built in Campus de Azurém of the University of Minho, where some of the advantages associated with the use of textile membranes and the design methodologies referred in this paper, were integrated and optimized. It can be concluded that there are good potentialities associated with the use of textile membrane materials that allow achieving a good environmental profile in innovative conceptions for modular housing.

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