Structures and Architecture – Cruz (Ed.)
© 2010 Taylor & Francis Group, London, ISBN 978-0-415-49249-2

Low-span lightweight membranes in housing – environmental and structural potentialities

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ABSTRACT: Textile membranes are usually used to cover big spans with complex geometries, using the special properties of the Hypar (Hyperbolic paraboloid). However it is possible to use membranes on small external façades and coverings, with low spans, not only as sandwich panels, but also as a junction of small Hypar modules. Like this the mechanical special properties of this geometry can be well explored, allowing a very small weight and thus a good environmental performance, compared to conventional façade and covering solutions, on a comparable thickness. Apart from this, the research on membrane materials for thermal regulation, allows to extend its possibilities in order to fulfill contemporary demands of comfort. In the outer skin, architectural membranes can be used as passive systems, for heating (promoting greenhouse effect) and cooling (shading or even evaporative cooling), as well as allowing some transparency, and thus also natural lighting, specially important on south and north facades. A prototype based on this concept is now under construction on Azurém Campus of the University of Minho, adapted for research on external façade systems as well as for coverings of small spans. This solution will be presented from its mechanical and structural concept, as well as its embodied energy and thermal / lighting performance, in comparison with conventional systems.

1 INTRODUCTION

1.1 *Membranes as functional performance regulators*

The fact of being the most lightweight constructive solution for facades and coverings used in buildings and nowadays having a life span that easily exceeds 25 years, specially when fluoropolymers are used, architectural membranes are becoming extremely competitive solutions, not just in mechanical and economical terms, but also in environmental aspects.

Conventionally, the external façades of a housing building are understood as “barriers” that separate the interior from the exterior, with well-defined areas of openings, the windows. Translucent textile based membranes can be an interesting solution to substitute this conventional façade concept, as they can cover the all building façade area with almost the same solar factor and thermal resistance, but with a most uniform distribution of solar radiation, both in thermal as in lighting. Membranes can actuate as diffusers of solar radiation, filtering it and limiting overheating and glare problems. Nowadays, transparent membranes with solar factors similar and even more favourable then conventional glass are encouraging new approaches to façade and covering design with membranes.

The need to save energy has brought a revaluation of the envelope’s role, and it is being increasingly conceived as a dynamic boundary, interacting with both external natural energy forces and the internal building environment. An interior ambient temperature can correspond to different resultant temperatures, according to the occupant's position and coexisting for a same space, different comfort situations. Homogeneity of the envelope, in terms of radiant sensitive heat and lighting imply a better control of thermal and optical comfort in all points where might be occupants.

In the same way that we can consider our skin “smart” for having reactive heating and cooling mechanisms, the introduction of active systems with adaptive capacities on the envelope of the buildings can allow lightweight constructions to have a functional performance that can in some aspects compete with conventional constructions. Mendonça (2005) also explored a strategy to combine lightweight and heavyweight constructive solutions and interior zoning, optimizing the overall functional performance of buildings, in a so called “mixedweight” solution.

Membranes can take several roles on the thermal control of buildings, as shown on Figure 1.

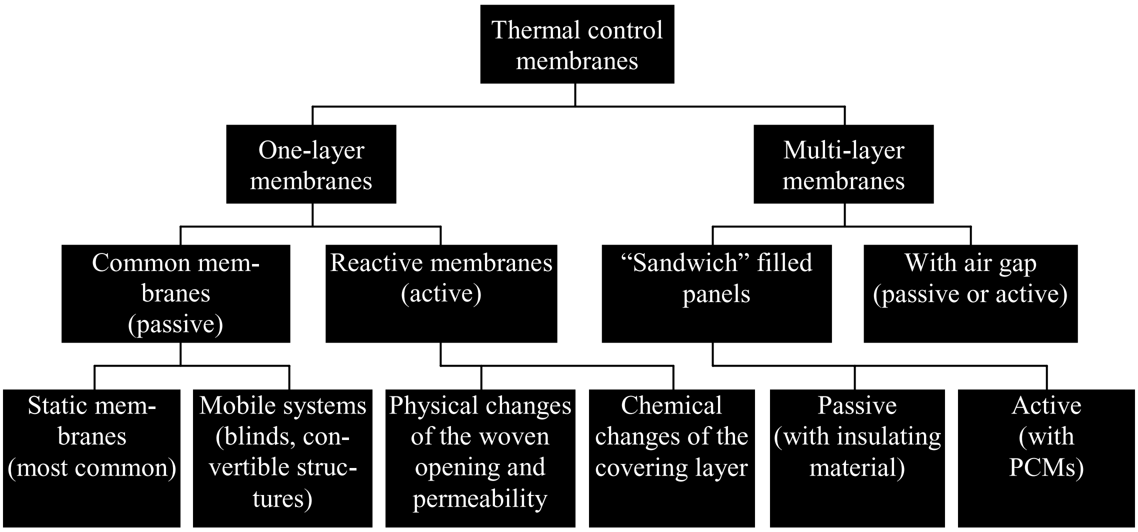

Figure 1. Classification of Thermal control membranes (Mendonça, 2005).

1.2 *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" (Horden, 1995) 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 specially 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 weigh approximately 2 - 3.5 kg per square meter, 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 (Robinson, 2005).

1.3 *Cube Prototype in University of Minho*

A test cell where the environmental and structural potentialities of low span membranes can be explored is constructed on University of Minho, on its Campus de Azurém, Guimarães. This prototype is composed by two modular cubes joint together with 2,5 x 2,5 x 2,5 m (Figure 2a)), expandable in south façade. Its main structure is made of aluminium profiles of 70x70mm, which section can be seen on Figure 2b). The west and east façades are made of an opaque white polyester/PVC membrane of 2,5 x 2,5 m fixed to the aluminium profiles by a PVC rod. Its structural stability 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 2c)), that also assure the cross stabilization of the panels. The same system is reproduced on the covering, 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. The functional concepts to be tested are above exposed in this paper.

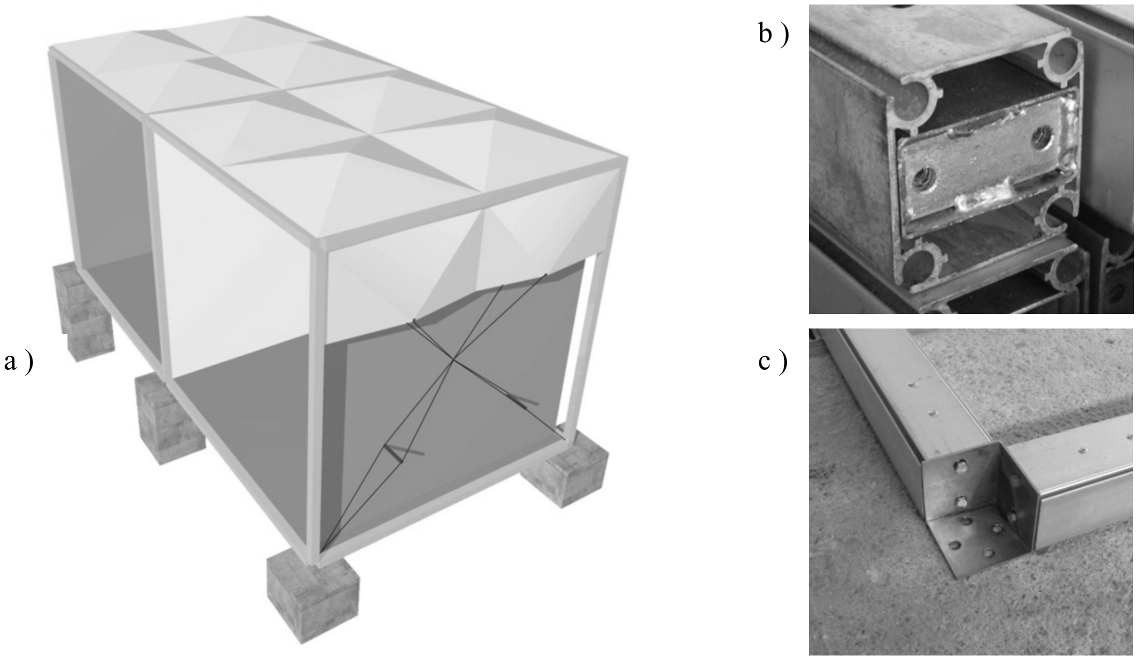

Figure 2. a) overall view of test cell facility (Drawing by Alex Davico), b) aluminium frame profile section, c) steel joint connection on corners.

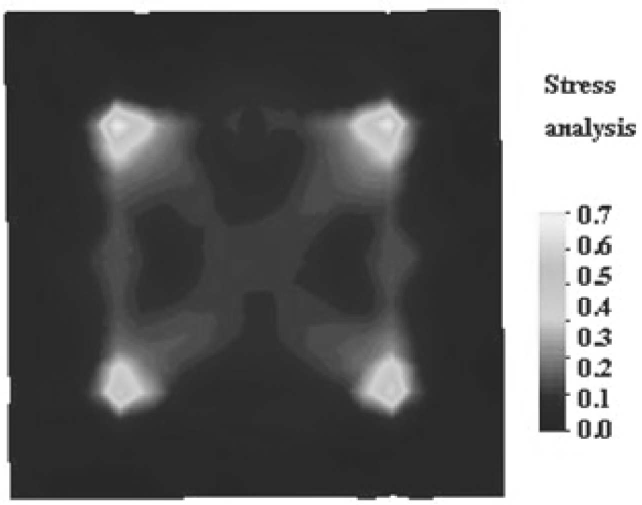

Figure 3. Computer stress analysis for form finding optimization.

Apart from conventional structural support elements in steel, aluminium or wood, the use of pneumatic membrane trusses can also be pondered, in order to achieve even more lightweight façade panels, thus more portable e adaptable to diverse uses and situations.

2 MEMBRANES AND SUSTAINABILITY

2.1 *Lightweight means sustainable*

Berge refers that "(…) the amount of energy that actually goes into the production of building materials is between 6 and 20% of the total energy consumption during 50 years of use, depending on the building method, climate, etc" (Berge, 1999). This is not the most relevant percentage, even if we consider the maximum, but energy cost in 50 years will be higher, and the dismantling, treatment and transport of waste materials also represents energy, especially in nowadays most common constructive system used in South European housing – concrete structure with hollow clay brick walls and pavements.

The minimum use of materials in buildings implies a minimum overall weight of building and so smaller damages due to the extraction of raw materials, to their transformation processes, to the work yards, with reduction of the noise, dust, wastes and the consumption of energy during the construction and a proportional reduction on loss factors and on transport energy cost. We should have in mind that a road transport by truck implies 440kWh/kg/km, and that is the most used transport way for construction materials. With a lightweight solution the reduction of weight can easily be of more then 90%, and even with a mixed-weight can be of almost 50%, with consequent reduction on Embodied Energy and Transport Energy that allow an overall energy cost reduction of approximately 60%, although maintaining the functional performance in equivalent levels, as it was concluded in previous studies (Mendonça, 2005).

Table 1. Relevant properties of some translucent and transparent materials.

	Visible Light Transmission	Weight (kg/m^2)	Embodied. Energy (kWh/m^2)	Thermal Resistance (vertical plan) (m^2.°C/W)
Clear Glass 6mm	85%	14.40	73.6	0.16
Idem Double 6(10)6mm	70%	28.80	147.2	0.35
Polycarbonate Clear panel (10mm)	83%	2.00	48.4**	0.32
PVC coated polyester (0,5mm)	26%	0.84	18.3**	0.17
idem, two layers with air gap of 15mm	n.a.	1.68	36.6**	0.37
PTFE Coated fibreglass	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) 1710Kg/m^3	95%	0.34	4.83	0,16
idem, two layers with air gap of 100mm	n.a.	0.64	9.66	0.35

*R.E. Shaeffer

**Deduced values by Mendonça (2005) (considering just the embodied energy to make the two components of the material and excluding manufacture)

Table 2. Embodied Energy Savings by recycling Materials (Mumma, 1995).

Energy saved by using recycled materials (%)	
Aluminum	95
Plastics	88
Glass	5

Source: Roberta Forsell Stauffer of National Assistance Service, published in Resource Recycling, January / February 1989**.**

The use of membranes and polymeric foils in lightweight façade and coverings could be understood as "smart", not just in structural terms but also regarding their embodied energy, when comparing them to glass. Even if it is considered that their life span could be half of glass, their significantly lower specific weight (for an equivalent thermal resistance) makes these solutions very competitive in terms of its production energy and transport costs, what can be seen on Table 1. As it can be seen on the same table, thermal resistance is not a problem with polymeric membranes, as they can easily present better thermal resistance then glasses. But of course, a greater thermal resistance necessarily implies a loss of visible light transmission.

As it can be seen on Table 1, an ETFE foil can weigh 40 times less than any transparent glass alternative and uses approximately 15 times less embodied energy per square meter.

Polymer producing technology also allows a higher recycling potential (88%), but of course this is more truth with thermoplastics. New technologies for recycling thermofixed polymers are now under research and application promising high expectations for the future. Apart from this, the energy saved by using recycled plastic is much higher then the energy saved by using recycled glass, as it can be seen on Table 2.

3 PROPOSED MEMBRANE CONCEPT

The proposed membrane concept for the external south and north façades will focus three main aspects: translucent and/or transparent layer that assures waterproof and solar passive gains, shading devices to regulate thermal exchanges and control natural lighting, using the structural optimized concept previously referred on point 1.2. Cross ventilation is also an important aspect, that can be assured by opposite north/south façade openings.

3.1 *Translucent/transparent waterproofing layer*

Generally, membranes are translucent, but not transparent; they are in most cases composites with a textile based structure (such as polyester and fiberglass) with a polymeric covering, such as Polyvinyl chloride - PVC, Polytetrafluoroethylene - PTFE or Silicon.

In spite of their ideal properties to achieve a good protection from excessive solar radiation in hot climates during the day, common membranes (such as the Polyvinyl chloride PVC coated Polyester) are characterised by a low visible light transmission and a low thermal insulation. Juxtaposition of two or more membranes with an air gap can increase thermal resistance to equivalent or higher values than double pane glasses, especially when the air gap between layers is filled by translucent insulating materials (such as fibreglass), but loosing, even more drastically, its translucency, already much lower then glass.

One of the first plastic materials that can be comparable with glass in terms of transparency was PMMA - Polymethyl methacrylate, brought to market in 1933 and commonly called acrylic glass. Apart from its good mechanical and chemical resistance, PMMA present an equivalent refraction to clear glass. One of the first relevant and famous uses of acrylic in membrane construction was made in the covering of the Munich Olympic Stadium from Günther Behnisch and Frei Otto, shown on Figure 4. But this was really a cable net structure, as this material was not suitable to be used as structural membrane. A recent material is now capable of solving this problem, the Ethylene-tetrafluorethylene (ETFE), used in membranes it presents a great translucency and a good Thermal Resistance in relation to its thickness. As it is a fluoropolymer, ETFE has a long durability, is self-cleaned by rain and weights much less then glass, so it can also be used to achieve thermal gains on permanent structures. It is made of homogeneous polymer foils and it is being largely used nowadays, especially in double layer cushion solutions, such as in the Eden Project tropical greenhouse from Nicholas Grimshaw located in Cornwall, England or the most recent "Water Cube", the Swimming pool for the Beijing Olympic games.by PTW Architects and Ove Arup The Allianz Arena Stadium in Munich, from Architects Herzog and De Meuron also contributed to make this material so popular. In this last project, transparent and opaque ETFE membranes are combined in the roof to allow sun to reach the playing field, but not the spectators.

This material can be as transparent as extra-clear glass but at the same time exhibits excellent mechanical toughness and a chemical resistance that rivals Polytetrafluoroethylene (PTFE). In addition, ETFE exhibits a low conductivity and can withstand moderately high temperatures for a long period of time without loosing significant mechanical resistance, what makes it an ideal material for membrane structures where high transparency is needed in a structural membrane. The greatest problem of PTFE, as well as other polymers, is that its emissivity is much higher then glass, what don't promote a so significant greenhouse effect. But low-emissivity coatings are now being studied and already marketed by some membrane producers, so this problem is already being solved.

Figure 4. Munich Olympic Stadium from Günther Behnisch and Frei Otto.

Hannover Expo 2000 Japan Pavilion from Shigeru Bahn can be understood as an ecological approach to accomplish the Expo pavilion function, using a special water-proof translucent membrane, and a recycled paper tubes structure weighting only a small part of what could weight a steel or even timber structure (that could already be considered lightweight structural solutions) and thus having a much smaller environmental impact and even allow being almost totally easily recyclable and with a reduced economical cost. This project was also made with Frei Otto as Consulting Engineer and it is a good example of a new attitude, suggesting the hypothesis of giving to existing materials new possibilities.

Frei Otto also developed several studies on bionic architecture, in that nature serves as model to the conception of construction materials, structures and subsystems based on organic natural forms. Increasing research on the concept of the adaptive capacities can conduce to buildings that breathe in function of the climatic conditions or of the lighting conditions. In order to avoid conflicts between Winter and Summer specific needs, some active variable or controllable properties can be developed on translucid/transparent façades, such as:

- Phototropic: the transmissivity of these systems depend on the incident radiation intensity, when higher this is, lower becomes transmissivity. This effect is not desirable in winter for passive solar gains;
- Thermotropic: in thermotropic systems, transmissivity varies in relation with temperature. This is already a system whose function principle is more interesting in what respects solar passive gains, if the material can remain transparent above 20ºC;
- Electrochromic: transparency property of this façade system can be controlled by two electrodes separated by an ion conductor. Electrochromic materials undergo a reversible change in optical properties.

The introduction of more efficient then glass translucent materials permit, not just the reduction of weight in transport, but also in embodied energy cost per m2 of façade, when compared with glass, as it can be concluded from the analysis of Table 2. Architectural membranes with just a few millimetres thickness constitute a self-portable material and either can be translucent for solar passive gains, as well as shading devices that protects from excessive solar radiation, or from ultra-violet rays.

The concept of Translucent insulation appeared in façade systems, as solutions that have an U-value between a double glass and a conventional wall (i.e. between 0,5 and 1,1W/m2.ºC). Transparent insulation materials can be classified over its geometric construction in four types:

- Absorbent/parallel: it consists in layers transversally superposed and in some cases with low-emissivity interior coatings. Its effectiveness is low, because the percentage of reflected energy is high, by the sum of reflections in the various leafs (Figure 5.a)) (as in double or triple glasses);
- Absorbent/perpendicular: it consists in tubes or layers perpendicularly posed in relation to the plan of the element. This system allows high solar passive gain efficiency because reflections

allow radiation to pass through the element with low sun heights in winter and avoid it in summer (Figure 5.b));

- Porous/cell structures: The solar passive gains are low, but they can allow a good compromise between thermal and acoustical insulation (cell structures; translucent foams, fibreglass);
- (Quasi-) homogeneous: characterized by a good thermal insulation but not so good acoustical absorption. This system is similar to the previously described, but the cell composition is closed and generally not apparent (e.g. gel - colloidal system in which a porous network of interconnected nanoparticles spans the volume of a liquid medium).

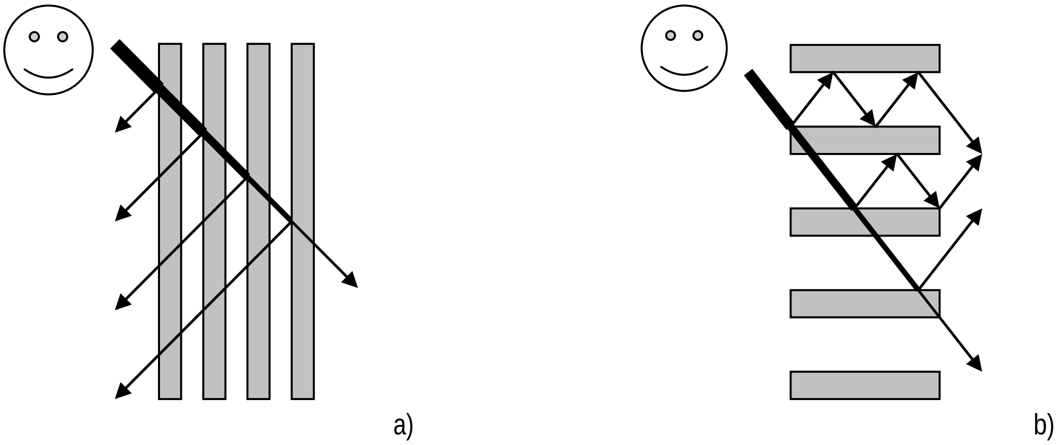

Figure 5. Parallel and perpendicular transparent insulation geometric constructions.

3.2 *Shading*

High insulation is not, by itself, effective, and can even be problematic on temperate climates. Shadowing is essential for a good thermal performance and for that the characteristics of the shading devices should obey to certain rules, namely to have in mind solar charts for each location. Shadowing can be made naturally, using vegetation that can even have an active role. It can also be artificial, by the relative position to other constructions or by the volumetric form of the construction. Shading should also be pondered (metallic, concrete and wood), but also textile elements, as awnings, with the additional advantage of a reduced weight and being possible to obtain several transparency degrees to solar gains. The efficiency of shading devices depends on its position in relation to the translucent waterproofing layer.

Table 3. Solar factor of simple glass windows with internal and external protection

	Colour of protection				Colour of protection		
Type (interior protection)	white	med.	dark	Type (exterior protection)	white	med.	dark
Clear glass 6 mm		0,85		Clear glass 6 mm		0,85	
Venetian blind				Blind	0,45	0,56	0,65
Timber	0,05	0,08	0,10				
Metal	0,07	0,10	0,13				
Screen				Curtain			
Opaque <5%	0,07	0,09	0,12	Opaque <5%	0,33	0,44	0,54
Transparent 15-25%	0,14	0,17	0,19	Transparent 15-25%	0,38	0,48	0,58
Very transparent >25%	0,21	0,23	0,25	Very transparent >25%	0,70	-	-
Timber	0,04	0,07	0,09	Timber	0,30	0,40	0,50

Source: RCCTE – Portuguese Thermal Regulation, 2006

4 CONCLUSIONS

This paper shows the concepts behind a membrane construction prototype being built in Campus de Azurém of the University of Minho where some of the aspects referred in this paper are being integrated and optimized.

Architectural membranes are nowadays used with competitive costs for covering big spans, but they can be also suitable for small dimension constructions, even for housing. This paper intends to show the potentialities and challenges associated with the use of lightweight materials, in order to achieve a good environmental profile, allowing its use in innovative design conceptions in temperate climates.

The examples presented in this paper shows how easy is to improve environmental performance of constructions just by using effective membrane solutions. In spite of the increasing evolution that membrane materials achieved in the recent past, there is still a long way to go through, before these can be accepted and can be considered as sustainable, especially regarding social and cultural resistance when it regards to housing. In spite of the fact that lightweight materials and solutions are environmentally suitable to be used in bioclimatic constructions, as it is shown, even in temperate climates as the south European ones, these are only being timidly implemented and their possibilities are not completely and positively explored.

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