Membrane structures with improved thermal properties

Michael Karwath*

* Wagner Tragwerke
Structural Engineering and Design
Sterneckerstrasse 16A D-70563 Stuttgart
fon +49 711 8825 918 fax +49 711 8825917

Key words: Multilayered membranes, thermal active membranes, thermal behaviour .

Summary. Typical for single layer membrane structures is the less isolation against temperature and sound. A demonstration building is developed to demonstrate the possibilities of membrane structures being more environmental and sustainable for conditioned indoor use. The solar and thermal principles of the basis of the skin of the ice bear are converted in the technical solution of a membrane structure. A membrane structure is developed based on a translucent multi layer, double curved and pretensioned system with high thermal isolation properties. The demonstration building shows different solutions of membranes with improved isolating properties.

The structural task is the development of a multi layer, double curved membrane with layers of different stiffness, load carrying and environmental properties. The different solutions of coupled layers are designed and analyzed. This includes the design of the membrane in relation to the different mechanical and thermal properties of the single layers as well as the mechanical connection of the layers. The main aspects are the position of the load carrying layer and the load carrying connection between the layers and the influence of the different temperatures of the single layers to the load carrying behaviour of the total system. Furthermore it needed to be examined the influence of enclosed air if one solution has an inner and outer load carrying layer similar to an inflated structure.

The design steps towards a demonstration building are presented which are divided into the examination of the membrane materials available on the market for the functional layers, analysing of different layouts of the functional membranes, design proposals for the demonstration building and detailing of the multi layer system including the thermal active membrane and thermal isolation. Advantages and disadvantages of the different solutions are discussed considering air flow, load carrying behaviour, detailing, long term behaviour and mounting on site.

1 INTRODUCTION

The target of the presented design project is tied together the theoretical knowledge of the fields textile of materials, structural design of m embranes, mechanics of enclosed gas vol - umes and thermodynamics of heated gas flow, with the technological experience concerning energy technology, supply techno logy, connecting methods, cutting p attern and practical know-how with regard to m anufacturing new and efficient use of solar energy in mem brane structures.

The actuality of the design lies in developing ne w ways to the use of solar energy, m ini- mizing the use of fossil fuels for heating and cooling of buildings. The presented design is also suitable to rearm existing buildings with a lightweight second skin increasing the thermal isolation and having the potential of harvesting solar energy.

In the presentation a textile building is devel oped with all necessary structural components including a gas layer w hich can heat up with high solar irradiation on 100° C to 150° C is incorporated actively in the energy balance. This encloses the production of energy from the hot gas layer, preventing the sola r radiation in the in terior and cooling out in cold winter nights. The design is a cooperation of several companies and ITV Denkendorf.

ITV Denkendorf has developed on the solar-therm al functions of the polar bear' s fur spac- ing textiles which connects the flexibility of a fibre-reinforced material with a translucent so- lar insulation. The knitted spacing f abric is ab le to let the s unlight though to an tex tile ab- sorber which transfers visible and UV-light into hot gas. The gas is guided in canals to energy storage system, figure 1.

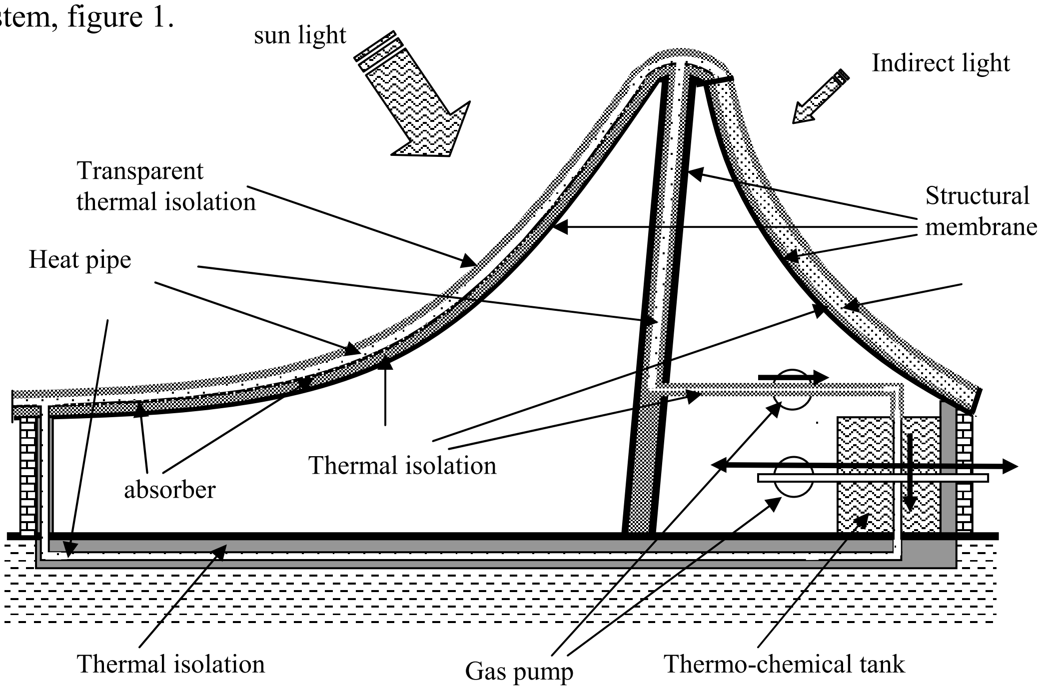


Figure 1: Design of a textile building for energy harvesting

2 MATERIAL REQUIREMENTS

The design of a multi-layer membrane is examined which is used for harvesting of solar energy and requires a higher thermal resistance than usual membranes in the textile architecture such as coated fabrics or foils made of polymers. The multilayer system for harvesting of solar energy is called subsequently functional membrane.

For demonstrating the capability of the textiles a free span of app. 10 m is given of the south side of the building. The surface is double curved in relation to the necessary pretension stress of the membrane avoiding fluttering or snow and water sags. This includes that all layers are made of flexible membranes, should have the same curvature and being pretensioned. Among the layers are several which are strong enough to carry the dead load of the thermal isolation, wind and snow. Depending on the layout the load carrying membranes needed to withstand temperatures up to 150 °C. For the load carrying layer fabrics of polyester and glass as well as ETFE foils are tested under higher temperature. The unidirectional tensile strengths of the polyester and glass fabrics lies between 60 kN/m and 100 kN/m and allows the span of 10 m. Differences between polyester and glass fabrics are the temperature expansion and temperature resistance. Usual polyester fabrics have an improved load-carrying capacity and suitability up to a temperature of 70°C. If polyester fabrics are used as load bearing elements, it should be made sure that the maximum temperature on the membrane surface lies under 70°C. Glass fabrics has a higher temperature resistance, the stiffness and unidirectional tensile strength shows are only little reduced up to temperatures of 150°C as result of tests carried out by the ITV Denkendorf. The absorber membranes is chosen as a silicon coated glass fibre fabric.

ETFE foils permit a maximum span of 1.0 m in mechanically pretensioned membrane structures and the location of the demonstration building is in the surrounding of Stuttgart. The values of the load-carrying capacity and suitability is given up to a temperature of 70 °C on the foil surface. If temperatures increases to more than 70°C in the functional membrane and the foils have, in addition, a load carrying function, investigations are to be carried out to get values for the unidirectional tensile strength and seam strength under higher temperatures.

The task needed to be solved is how high is the loss of pretension stress if the membranes is heated up to a surface temperature of 120° C. To grasp the influence of the temperature expansion on the load bearing behaviour, the following coefficients of temperature expansions and Young's Moduli are assumed, table 1. Even for the silicon coated glass fabric the pretension stress is lost if the temperature increase of more than 40°C and the membrane can only be used to carry the dead load of he system.

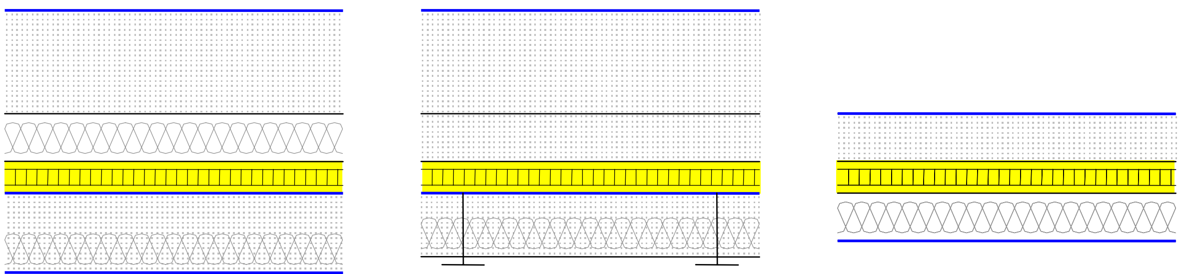
Membrane material	Temperature range	Coefficient of expansion	Youngs-Modulus kN/m warp/weft
ETFE-Foil	20 – 150 °C	$\alpha_T = 13 \cdot 10^{-5}$ 1/K	280/300
Polyester fabric	20 – 70°C	$\alpha_T = 7 \cdot 10^{-5}$ 1/K	800/1000
Glass fabric	20 – 150°C	$\alpha_T = 5 \cdot 10^{-5}$ 1/K	900/1200

Table 1: Data of the assumed materials

3 DESIGN OF THE MULTI LAYER SYSTEM

The lost of pretension under higher temperatures for any type of membrane material results in a system of multi layer membranes of an outer and inner load carrying membrane and the functional membrane in between. For the layout of the multi layer system several solutions are developed and evaluated. The functional layer for harvesting energy is designed as an ETFE foil on top, a black spacing polyester fabric and the black silicon coated glass fibre fabric. The layers above are to increase the thermal isolation with the constrain of having a high translucency. The layers below are to prevent heating up the inner space, the silicon/ glass fibre is hugh radiator and the heat should be kept in the spacing fabric. The different systems had been tested in a test equipment to increase the air temperature in the spacing fabric under radiation of 400 W/m² to 800 W/m². The air flow is given between 0 m/s and 0,6 m/s. The layout which turned out be feasible for energy harvesting are shown in figure 2, the most favoured one is layout 2 concerning the layers above the functional layer. The thermal isolation in layout 1 reduces the light coming to the absorber and in layout 3 loss of temperature is higher.

Layout 1 | Layout 2 | Layout 3



Layout 1:
- ETFE-foil with cables
- Layer of air
- ETFE-foil
- Thermal isoaltion translucent
- Functional layer
  - ETFE-foil
  - Spacing fabric, black
  - Silicon/glass fabric, black
- Layer of air
- Thermal isolation
- PVC/Polyester fabric

Layout 2:
- ETFE-foil with cables
- 1st layer of air
- ETFE-Foil
- 2nd layer of air
- Functional layer
  - ETFE-Foil
  - Spacing fabric, black
  - Silicon/glass fabric, black
- Thermal isolation, suspemded
- PVC/Polyester fabric, suspended

Layout 3:
- ETFE-foil with cables
- 1st layer of air
- Functional layer
  - ETFE-Foil
  - Spacing fabric, black
  - Silicon/glass fabric, black
- Thermal isolation
- PVC/Polyester fabric

Figure 2: Layout of the membrane structure

The test equipment has a span of 0,5 m and a length of 4 m and the target is to bring this layouts to a free span membrane structure of app. 10 m x 10 m. Possible layers to carry the load over the assumed span are coloured blue in figure 2. To earn very high profits from the solar irradiation, the ETFE foils which are permeable for 99% of the visible light and ultraviolet rays are suited. The disadvantage of ETFE foil is the less strength and the top layer is reinforced by additional polymer coated steel cables. The size and the distance of the steel cable is defined by carrying the external loads such as snow and wind. The distance to the next ETFE foil is given to avoid convection of the air in the gap on the one side and to prevent contact under snow on the other side.

Designing the absorber membrane as load carrying element for a span of 10 m means to take into account the change of the sag under different temperature ranges. It is assumed temperature drops to 10 °C in a cold winter night and increases to 150 °C in hot summer days. These temperature range causes a change of the length of 0,7 % for a span of 10 m which seems to be relative less. The change of the sag is related to the curvature of membrane and a elongation of 0,7 % may increases the sag of the membrane, see table 2.

Span	sag	Temperature Elongation	sag incl. temp. elongation	difference in the sag
10,00 m	0,00 m	0,7 %	0,36 m	0,36 m
10,00 m	0,20 m	0,7 %	0,55 m	0,35 m
10,00 m	0,50 m	0,7 %	0,72 m	0,22 m
10,00 m	1,00 m	0,7 %	1,12 m	0,12 m

Table 2: Influence of the temperature elongation to the sag of a membrane

In case the layer above are connected to the functional layer, these layers have to be able to fulfill the same deformations. The two other solutions are shown in layout 1 space between the absorber membrane to avoid contact or the absorber membrane lays on the thermal isolation and has no load carrying function, layout 3. In layout 1 the air gets hot between the absorber membrane and the isolation leads to an internal pressure because of the closed gas volume necessary for the required tightness. In layout 3 a solution needed to be found how to fix the functional membrane onto the inner membrane and tension the whole package.

The different polymers for the functional membrane make it hardly possible to laminate the ETFE foil to the polyester spacing fabric and the spacing fabric to the silicon coating of the glass fabric. The connection of the membranes to the spacing fabric is only possible mechanically either by using snap clips, clamps or air pressure. Developed are two solutions in relation to the air flow through the spacing fabric. For energy harvesting the functional layer is divided into canals of a width of app. 0,5 m . Using a second layer of air above for thermal isolation this layer is also divided into canals. The ETFE foils and the absorber membrane have to be clamped air tight every 0,5 m. To prevent lifting of the foil from the spacing fabric the air pressure in the second has to be little higher than in the spacing fabric. This causes a controlled air flow not only in the spacing fabric but also in the air chamber above. Depending on the stiffness of the different layers and assuming an incompressibility of the enclosed air all layers are participating on the load carrying. The other possibility is sucking the air through the spacing fabric and the negative pressure holds the foil and fabric to the spacing fabric. This requires an air pressure in the second chamber in case of a hold up in the air flow between the spacing fabric. Numerical simulations are carried out to know the change of the pressure and temperature to the deflections and stresses in the different layers, see figure 3.

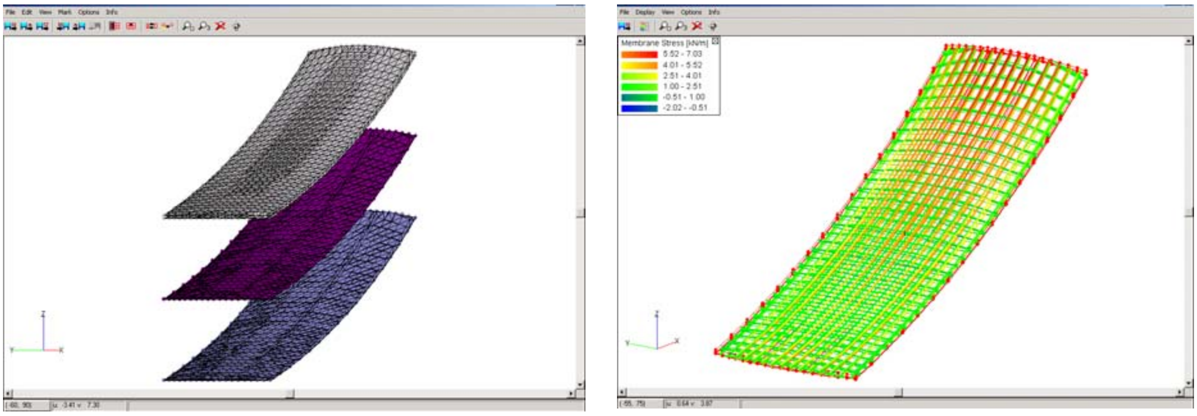


Figure 3: Three chamber system with four layer membranes

4 DESIGN OF THE STRUCTURE

The design of the demonstration building is defined by following parameter:

- The functional membranes is given by an area of app. 10 m x 10 m
- The span of the 100 m² is without supports, pretensioned and double curved
- The functional membrane is oriented to the south
- The inclination of the surface is between 30° and 40° related to the sun radiation of the location
- The lower and upper boundary is rigid to connect the membranes to the air supply system
- The functional m embrane is integrated in m embrane structure which encloses a inner space and can be used for exhibition and small conferences.
- Most of the roof and wall structures are designed as textile elements
- The parts of conventional elements such as glass facades are to be minimized
- The bending elements are as less as possible

Several proposal are designed and improved. Any type of saddl e shaped membrane has the disadvantage of integrating vertical facades or textile walls. Arches need either m ore space than required or the membranes are also orientated to east and west sides. Radial systems are less useful because th e functional m embrane has to rectangular shap ed with can als of the nearly the same width. Finally a solution com e up which fulfill most of the assumed requirements. The structure is based on two inclined ar ches and only the surfaces between the arches are made of rigid elem ents, the who le surface is made of textiles and foils. The outer m embranes are pulled of the inner layers and are responsible for carrying the external loads. On the south side the inner part is transparent and made of ETFE-foils with cables. On the north, east and west side the outer membrane is a high translucent PCV coated Polyester fabric, the inner fabric is on all sides a open mesh PVC coated Polyester fabric which carries the thermal isolation, The functional m embrane is of course tota lly opaque which requir es a certain translucency of the other parts of the structure to ensure working conditions for the day see figure 4.

The membranes and the steel arches are designed for 0,85 kN/m² snow load and 0.5 kN/m² wind load. Numerical calculations are carried out for the entire structures including the vertical and textile facades. One of the main topics of calculations is on the south side the influence of the thermal behavior of the membranes itself, the change in deflection in relation to the temperature and the interaction of enclosed gas volume. The air value in the single canals in very small and the air is assumed a incompressible which leads to an load transfer trough all layers under external loads, which is depending on the stiffness of the layers changing in relation to the actual temperature in the different layers and membranes.

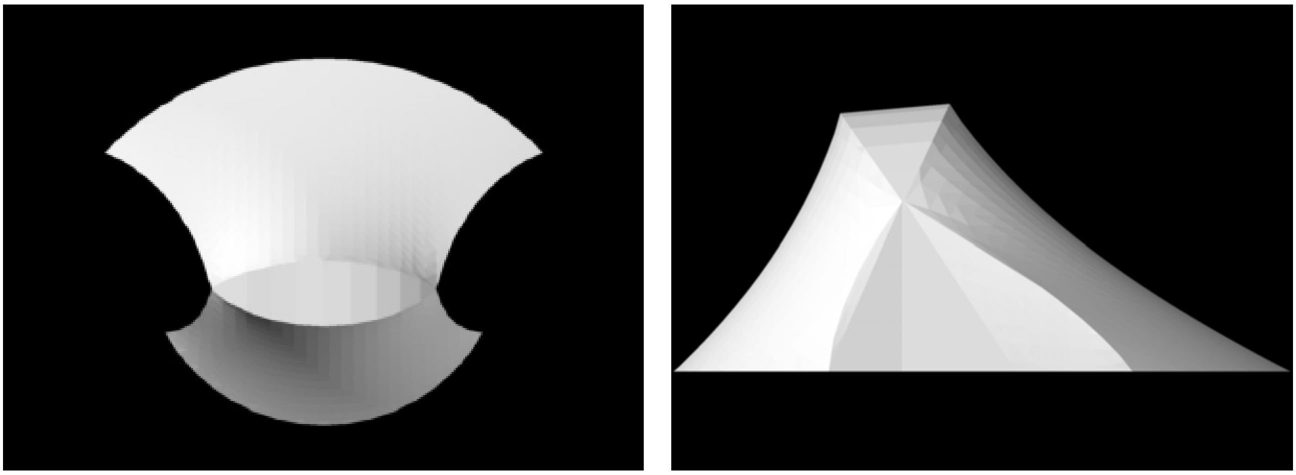


Figure 4: Design of a membrane structure for energy harvesting

5 CONCLUSION

- The design of membrane structure is present for harvesting solar energy
- The material chosen for the structure are discussed as well as the layout of the functional membranes is described
- The requirements for the structure are listed and the final design is shown.

6 ACKNOWLEGDEMENT

The paper presents part of the work within research project "Eisbärbauten" founded by the Ministry of Environment, Nature Conservation and Transport of the Federal State of Baden-Württemberg and the European Commission. The project partners are ITV Denkendorf, Arnold Isolierungen, Labor Blum, TinniT GmbH, TAO Technologies GmbH and Wagner Tragwerke.