The thermal behaviour of buildings incorporating single skin tensile membrane structures

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Abstract Membrane structures and the spaces they enclose offer significant opportunities to reduce energy consumption in buildings and associated carbon emissions. The nature and behaviour of this class of building differs so significantly from that of conventional buildings, it is important that appropriate predictive tools are available to assist in their design. This paper reviews the current literature on the environmental behaviour of membrane structures, presents new monitoring results obtained from field testing of a full size structure and proposes an approach to modelling the thermal behaviour of the system comprising the environment, a single skin membrane structure and the space it encloses.

Keywords tensile membrane structures; simulation tools; heat flow; energy; comfort

Introduction

Although the use of membrane materials to form small scale structures, such as tents, has been practiced extensively by many cultures, it was not until the development of saddle shaped fabric structures arising from the collaboration between the German architect Frei Otto and tent manufacturer Peter Stromeyer, that the enclosure of large spaces became a possibility. These first tensile membrane structures were only temporary, their life span being limited by the durability of the cotton canvas materials available at the time. Their use was therefore restricted to applications where protection from sun and rain was a primary function. As the targets for occupant comfort extended little beyond the requirement for shelter, it is perhaps unsurprising that while significant effort went into understanding the structural behaviour of tensile membrane structures and developing techniques and tools necessary for their design and manufacture, relatively little attention was paid to the environmental conditions created within the enclosed spaces.

Today, with the development of durable, high strength coated synthetic woven fabrics, such as PTFE coated glass fibre, and the continued development of sophisticated numerical methods for form-finding and structural analysis, the scale and durability of tensile membrane structures have increased to a point where they can outperform traditional construction materials. Increasingly complex permanent structures, such as the example shown in Fig. 1, are possible and tensile membrane enclosures represent an attractive architectural option.

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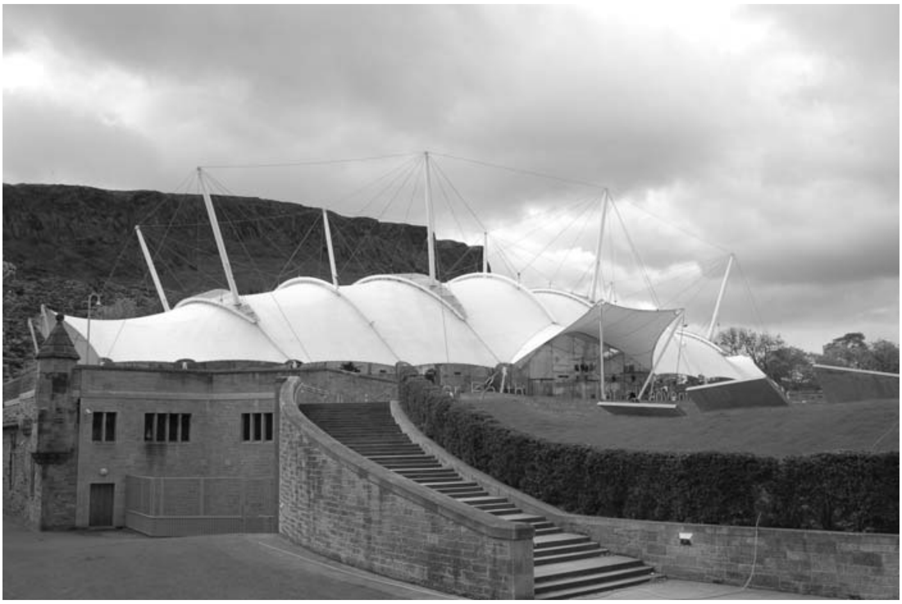

Figure 1. *Example of a membrane covered building.*

Current understanding of the environment created within the spaces enclosed by membranes is limited and represents a barrier to realising the full potential of this construction technique. Without the tools to quantify the degree of thermal comfort that might be experienced by the occupants of membrane enclosed spaces, the technique may be disregarded for applications where it might be perfectly suited, or adopted for applications where it is inappropriate. The latter case is perhaps the most serious, as occupant dissatisfaction could leave the technique with a poor reputation and a requirement for large space heating or cooling energy inputs to in order to achieve an appropriate internal environment. At their most basic, membrane structures can provide buffer spaces that protect buildings, or parts of buildings, from the extremes of the weather: a space that generally provides good levels of natural daylight and serves as an interface between a controlled indoor environment and fluctuating non-optimal outdoor climate. By protecting conditioned spaces from solar radiation and the effects of the wind within a large volume of enclosed air that is likely to lie at a temperature that is intermediate between the conditioned and external environment, there is significant potential to reduce the operation energy of buildings and the associated carbon emissions.

Field study work undertaken in the 1980s has provided insights into some of the underlying energy transfer mechanisms that help shape the environment within membrane enclosed spaces [1, 2, 3, and 4]. This work was supported by a combination of steady state and dynamic thermal modelling studies that sought to quantify the thermal behaviour of membrane structures using tools designed for buildings of conventional construction [2, 5]. Simplifying assumptions implicit in these models meant that some of the important heat transfer phenomena observed in field study data could not be accounted for, with the consequence that their results did not provide a full picture of their thermal behaviour. The advent, in the 1990s, of tools such as Computational Fluid Dynamics and the availability of inexpensive computers upon which to run software, provided an opportunity to advance the field. Using these, Harvie [4] has undertaken perhaps the most comprehensive study of the environmental behaviour of membrane structures. This work indicated that the thermal behaviour of the system comprising the environment, membrane structure and the space it encloses is complex and is likely to require the application of a number of analytical and computational approaches if it is to be fully understood.

This paper draws upon existing research to describe the important mechanisms responsible for energy exchanges between membrane enclosed spaces and the external environment occurring via the membrane itself. Existing and new data obtained from field testing of membrane structures help describe the behaviour of the enclosed space in response to these energy exchanges and to identify the key features that any simulation tools should take account of. It concludes by outlining a modelling approach that, if adopted, may allow designers to understand and explore the behaviour of this class of structure.

Thermal properties of membrane materials

The factors that control energy flows through membrane structures differ significantly from those in conventional building structures. It is useful to understand what these differences are before proceeding to review previous work that has explored the monitoring of membrane enclosed spaces and simulation of their thermal performance.

Modern membrane materials are superior in both strength and durability to their canvas predecessors and have enabled the increase of the physical scale, and perhaps as importantly, the service life of fabric structures. Because most fibre materials experience significant degradation under weathering, the development of architectural membranes is based upon the combination of high tensile strength woven fibres, such as polyester or fibreglass, with synthetic coatings as indicated in Fig. 2. The coatings provide air and waterproofing of the tensile membrane skin, whilst protecting the fibres from the effects of UV radiation, abrasion and atmospheric chemical attacks. Traditionally PVC coatings were used; however, early products were susceptible to discoloration and had limited lifetime. The addition of PVDF top coats helped to counter these limitations. More recently coatings such as PTFE and silicone have expanded the range of fabrics available to the designer. A detailed description of this range of membrane materials can be found in [6], however, this paper concentrates on the popular translucent fabrics that usually employ PVC or PTFE coatings.

Energy flows through these typically white or cream coloured fabrics are dictated in large part by their optical properties. When light is incident on these materials, part of the flux is reflected, part is absorbed and the remainder is transmitted. Sample short wavelength data for PVC and PTFE membrane materials are shown in Fig. 3.

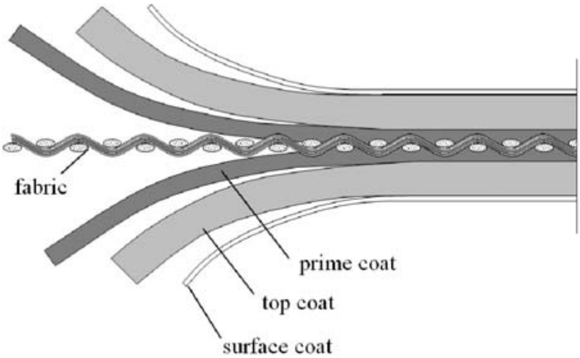

Figure 2. *Make up of a typical coated woven fabric membrane (after [6]).*

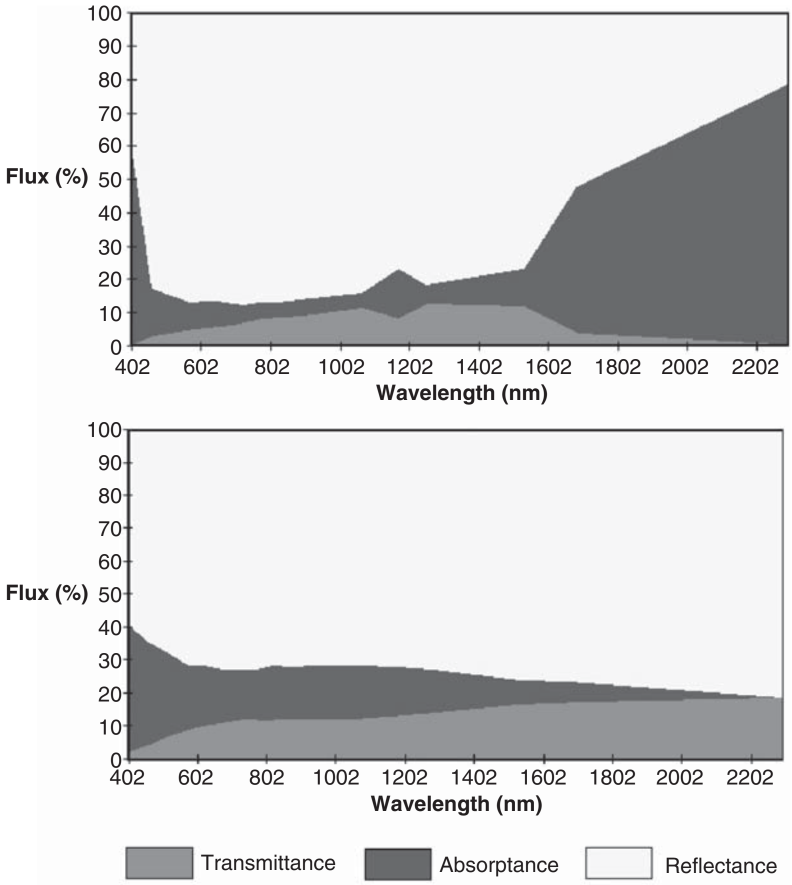

Figure 3. *Near normal solar optical properties of Type 2 PVC coated polyester (left) and weathered Type 1 PTFE coated fibreglass (right) (after [4]).*

Table 1. *Comparison of the thermal properties of different roof constructions.*

	Concrete Heavyweight, dry	Single glazing Toughened glass	Coated membrane PTFE/glass
Thickness (mm)	300	10	0.8
Surface density ($kg{\cdot}m^{-2}$)	720	25	1.72
Specific heat ($kJ{\cdot}kg^{-1}{\cdot}K^{-1}$)	0.84	0.72	1.2[a]
Heat capacity ($kJ{\cdot}m^{-2}{\cdot}K^{-1}$)	604	18	2a
Core conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	1.3	1	0.19[b]
Core thermal resistance ($m^2{\cdot}K{\cdot}W^{-1}$)	0.23	0.01	0.0042
Total thermal resistance ($m^2{\cdot}K{\cdot}W^{-1}$)	0.37[c]	0.15[c]	0.14[d]
Core resistance as % of total thermal resistance	62%	7%	3%

Notes: [a]assuming solid PTFE only, [b]taken from Hirokazu et al. [8], [c]assuming average surface resistance design values taken from BS EN ISO 6946 [7], with external surface resistance $R_{se} = 0.04$ and internal surface resistance $R_{si} = 0.1$ (both values for ceiling/roof), d taken from Hirokazu *et al*. [8], at 20°C with air velocity of $1\,m{\cdot}s^{-1}$.

These indicate reflection from the external surface plays a significant role in controlling solar energy flows incident on a membrane. Direct solar gains, while smaller, are still significant with typical transmission to the enclosed space in the region of 5% to 10%.

In addition to this direct energy flow, the membrane also influences indirect energy exchange between the external environment and the enclosed space whereby solar energy absorbed by the membrane is transferred to the interior by processes of convection and radiation. This is in addition to heat flows driven by air temperature gradients between the enclosed space and the external environment. An inevitable consequence of this lightweight form of construction (the thickness of architectural membranes is typically about 1 mm), is the very low heat capacity of the building skin. This means that, in comparison with conventional construction materials (such as those presented in Table 1), the membrane reacts extremely quickly to external heat inputs, such as absorbed solar radiation.

Although modelling the thermal behaviour of such a lightweight material does not represent an insurmountable problem *per se*, it does imply a move away from the way in which the construction industry has traditionally represented building fabric heat flows. To date, membrane manufacturers have described the thermal properties of their products through use of the U-value, which is appropriate for materials where heat transfer is controlled by conductivity. The U-value, or thermal conductance, U, represents the amount of heat conducted through a material as the result of a temperature difference of 1°C across its faces. This is expressed in W/m^2 K and is calculated for a simple single skin element as follows [7]:

$$U = \frac{1}{R_{si} + \frac{d}{\lambda} + R_{se}}$$

$R_i = d/\lambda$ core thermal resistance of element (m^2K/W)
R_{si} R_{se} combined radiative and convective thermal resistance of the internal and external surfaces respectively (m^2K/W)
d thickness of the element (m)
λ core thermal conductivity of the element (W/mK)

The core thermal conductivity (i.e. the conductivity of the material from which the element is made) is assumed to be independent of temperature yielding a constant value for the core thermal resistance. Fixed values of surface thermal resistance, R_{si} and R_{se}, are selected reflecting the orientation and degree of exposure of the material surfaces.

These surface thermal resistance terms describe the complex heat exchange processes occurring at the material boundary and comprise the sum of the radiative heat exchange between the surface and its surroundings and the convective heat transfer occurring at the material/air interface. Because of the difficulty in calculating these phenomena, a number of simplifying assumptions are normally made. Both surface thermal resistances are assumed to be independent of the surface temperature itself and are quoted based on fixed temperatures for surrounding surfaces [7].

For this reason British building regulations assume that the core thermal resistance should account for at least 94% of the overall thermal resistance of an envelope component, in which case the U-value is a fairly accurate representation of its conductance. This implies that for conventional construction types, such as the insulated flat roof in Fig. 4, variations in surface thermal resistance tend to be small in comparison with the core resistance, and so may be neglected with an acceptable loss of accuracy in the description of their thermal performance.

In practice, the core thermal resistance, and hence the thermal gradient through the membrane core has been found to be negligible [8], leaving a U-value that is dominated by surface thermal resistances, as indicated by the data in Table 1.

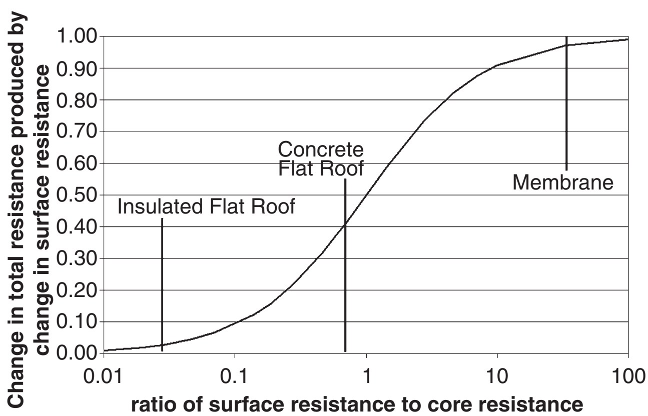

Figure 4. *Relative importance of surface resistances for typical construction types.*

Temperature fluctuations observed on membranes in response to changes in incident solar radiation mean that for this class of structure, the measured surface thermal resistances demonstrate strong and rapid variability depending on both the surface temperature and the air velocity near the surface [4]. In 1984, Hirokazu et al. [9] attempted to measure the heat transfer rate at the surfaces of a series of coated woven membranes, and demonstrated that they are highly sensitive to environmental conditions. For a fixed temperature difference between the membrane surface and the surrounding air of about 12°C, *the surface thermal resistance* varied linearly from 0.08 m^2K/W at 1 m/s to up to 0.04 m^2K/W at 4 m/s. A dependency, although less marked, between surface-to-air temperature difference and surface thermal *resistance* was also highlighted, with the surface thermal resistance decreasing by 20% as surface-to-air temperature was increased from 5°C to 25°C, due possibly to the increased natural convection. Changing the emissivity of a blackened sample of membrane by silvering the surface yielded resistances that increased by around 25%, indicating that long wavelength radiative exchange also played a significant role in the surface heat transfer balance of the material.

As indicated by the data for the membrane in Fig. 4, assuming fixed surface thermal resistances for an element with a small core thermal resistance results in significant errors in the estimated total thermal resistance of the structure. Given that the total thermal resistance of the membrane skin depends almost entirely on the surface heat exchanges and, given that these are controlled both by the boundary layer formed by the air in contact with its surface and by the ability of the coated surface to control emission and absorption of radiation, a more sophisticated representation of the membrane is required. This needs to account for the rapid response of the membrane temperature with changes in the solar flux caused both by meteorological conditions and daily/seasonal variation in solar geometry. Such an approach is a significant departure from the steady state notion of thermal performance, traditionally held in the prediction of conventional structures and favours the adoption of a dynamic value that would be calculated depending on the instant environmental conditions surrounding the building skin as proposed by Harvie [4].

Characteristic behaviour of membrane enclosures

An understanding of the thermal characteristics of the membrane material, assists in understanding the thermal characteristics of membrane enclosed spaces, comprising the membrane roof, the enclosed volume of air and what is typically a thermally heavyweight floor slab. Monitoring studies undertaken on real buildings have helped provide insight into some of the mechanisms that influence the internal thermal environment.

In contrast to conventional structural systems using rigid materials, the geometry of tensile membrane structures is directly linked to the flow of forces in the surface. The surface of the membrane typically has to be doubly curved at all points to provide stability under environmental loads. Therefore the membrane skin needs to be deformed out of plane and this is achieved by providing a succession of high and low points in the membrane enclosure to generate the three-dimensional curvature.

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This implies that, if a wide space is to be covered without intermediate support, it is necessary to lift at least some points of the structure to substantial heights. Typical heights range from 30% to 100% of the total spanned distance. Consequently, clear heights often considerably in excess of 2 to 3 conventional storey heights are common in membrane enclosures. In addition, the deflections required to withstand environmental loads make membrane structures unsuitable for the support of intermediate floors or internal partitions. Thus, the spaces covered by membranes typically comprise a single zone, as the large volume enclosed by the membrane skin cannot easily be partitioned into sub zones. This has consequences in terms of air movement and temperature distribution within the space.

One of these is the potential for the establishment of a reservoir effect driven by stratification of buoyant warm air at the high points within the enclosure layers at human height. This phenomenon was identified by Wu et al. [1] who undertook a survey of the Unidome in Iowa, USA, focusing on variations in temperature vertically within the space. They observed the occurrence of stratification, with temperature differences in the order of 9°C between ground level and the reservoir of hotter air adjacent to the membrane at the top of the enclosure. This was found to follow a diurnal pattern and was attributed to the transmission of direct solar radiation and its subsequent release into the enclosure as well as indirect heat transfer from the membrane roof to adjacent air.

This migration of warm air to the top of the enclosure offers potentially more comfortable conditions resulting from cooler air collecting at ground level in the inhabited zone. Further, the high level hot air reservoir could be discharged through upper level vents and generate a cooling airflow in the inhabited zone driven by the stack effect. The stability of the upper layer could be viewed as being of benefit for thermal performance as it would tend to yield high surface thermal resistances on the internal faces of the membrane, which would help inhibit the convective exchange of further energy with the external environment.

Work undertaken by Croome and Moseley [2] investigated temperatures in the occupied zone of an air supported membrane structure in Bath, UK. Their results indicated that the temperature followed variations in both incident solar radiation and external air temperature, yielding internal temperatures that were higher than those prevailing outside during the day and colder than outside during the night. A parallel study by Croome and Moseley [3] explored the surface temperature of the membrane and indicated there were significant variations in temperature, with areas of membrane facing the sun attaining temperatures in the region of 40°C.

Harvie [4] undertook short-term monitoring of four membrane enclosures located in the UK. The results indicated that in the absence of solar input, the temperature within the enclosures was close to external air temperature. In the presence of solar radiation, vertical temperature stratification was observed, which, like Wu *et al*. [1], was attributed to solar gain as well as contrasting surface temperatures between the floor slab and the membrane roof. On clear nights, negative stratification of the internal air was observed with membrane surface temperatures in the order of 3.5°C below external air temperature being observed. During daylight hours, monitoring of surface temperatures indicated that the membrane could be as much as 20°C above ambient air temperature and that within a given enclosure, surface temperatures may vary in a range of up to 15°C. Rapid changes in membrane surface temperature, with rates of change as high as 5°C per minute having been monitored during changeable climatic conditions, were attributed to the thermally lightweight nature of the construction.

The results obtained by Harvie make it possible to postulate possible conditions that may occur within the enclosure. The complex geometry of the membrane, its relationship to the sun path and the highly responsive nature of the fabric mean that high contrasts in surface temperature can occur across different areas of the membrane skin caused by uneven exposure to solar radiation. This imbalance in the overhead radiative field is likely to be exacerbated by contrasts between the lightweight membrane and the thermally heavier floor slab or internal building walls occurring at lower levels. Consideration of this phenomenon is important in the assessment of thermal comfort. Significant variation in the radiant temperature field can be a source of discomfort to the occupant, a problem made worse for this building type by the large view factor resulting from the size of the enclosed space and the topology of the membrane. Variations in the radiant energy absorbed by the membrane could also drive convective flows that could result in occupant discomfort. For example on a cold day with strong solar radiation, large variations in the surface temperature around the envelope might induce rapid heating and cooling within different regions of the stratified layer and generate a strong downward flow of cooler air into occupied parts of the enclosure with an associated risk of occupant discomfort. Such flows would also serve to alter the surface resistances of the membrane structure and influence heat exchange with the external environment.

The collected body of monitored data indicates that the thermal environment inside tensile membrane structures is essentially characterised by its non-uniformity, both in terms of air and surface temperatures. These occur in large part because of the scale of the enclosed volume and the complexity of the membrane topology. While solar radiation penetrating the enclosure through the membrane skin plays a potential role in driving air flows within the space, the thermal state of the membrane skin, which is responsive to time and climatic variations in external radiation input is equally important. Indirect heat flows through the membrane are likely to be influenced by the thermal state of the membrane and changes to convective heat exchange mechanisms caused by flows within the enclosure. These observations suggest some of the key phenomena that should be accounted for in any attempt to simulate the thermal behaviour of membrane enclosed spaces.

Predicted behaviour of membrane enclosures

Early attempts to predict the thermal performance of textile constructions were essentially based on the steady-state approach where constant internal and external conditions are assumed. There are, however, three documented studies that have sought to use a more detailed description of the thermal behaviour of the membrane skin in order to predict the thermal behaviour of the space it enclosed. These studies used dynamic thermal modelling to account for the time varying response of the textile envelope to changes in internal and external conditions.

Croome and Moseley [2] used three dynamic thermal simulation methods (the admittance method, the response factor method and a finite difference method), to predict the air temperature inside an air supported membrane structure. While the three methods provided a detailed description of the dynamic heat flow through the membrane core in response to the dynamic climatic variations, they relied upon empirically derived surface heat transfer coefficients that were built into the models and were originally designed for thermally heavier constructions. Given this, the more detailed simulation of the conductive heat transfer through the membrane core would not be expected to significantly improve the modelling of the thermal behaviour of the textile skin as a whole, since the surface heat exchanges are likely to dominate the thermal performance. Internal air temperatures predicted using the three models were compared with monitored data obtained under similar weather conditions to those used as input to the simulations. The accuracy of the predicted temperatures ranged between 1°C and 6°C for the finite difference and response factor methods, while larger inaccuracies of up to 11°C were observed for the admittance method. This study did not constitute a significant improvement over steady-state methods, since the emphasis was placed on the modelling of the core conductivity of the thin lightweight membrane skin with the surface heat transfer simply treated using empirical combined heat transfer coefficients.

Hart et al. [5] carried out a simulation of the energy consumption of a retail space based on a modified version of the DOE-2.1A model [10]. The study sought to compare a conventional structure with single and double skin membrane alternatives. In the model, the membrane roofs were treated as large translucent windows and defined by five flat panels of equivalent surface area. Because the DOE model could only accept U-value and solar shading coefficients as input for the specification of the materials, these two properties were calculated using a finite difference heat transfer program. Hart et al. realised that the rate at which solar gains to the fabric roof would be lost to its surroundings by convection would depend on the varying heating and cooling conditions assumed for the enclosed space. Two alternative sets of U-values and shading coefficients were therefore calculated and selected depending on the assumed internal loads. In addition, an empirical external heat transfer coefficient based on wind speed was implemented to provide a more realistic simulation of the external convection. The results of the analysis highlighted that the savings on artificial lighting allowed by the translucency of the membrane constructions could balance the additional costs required for heating and cooling. In particular, single-layer membrane roofs were shown to outperform a conventional roof in terms of energy efficiency in warm areas, whereas a double-layer membrane roof would perform as well as a standard roof in cold climates. Although the approach of Hart et al. attempted to account for the variability of the thermal behaviour of the textile constructions by the use of alternative combined heat transfer coefficients for different load situations in the enclosed space, the success of such an approach is difficult to evaluate, since no attempt to validate the model was reported.

While the previous models where based on the assumption of uniform internal air temperature distribution, the development of Computational Fluid Dynamics (CFD) techniques for applications in the built environment during the 1990s provided the possibility of a more detailed description of non-uniform internal conditions. Harvie [4] proposed use of the technique for predicting the behaviour of membrane structures, and undertook detailed modelling of the heat transfer process occurring at the surfaces of the membrane. In order to produce realistic boundary conditions for the simulation, a detailed thermal model was used to predict the thermal state of the membrane skin. This was based on the assumption that the thermal mass of the membrane was negligible and hence it would respond instantly to changes in its environment. Long-wave radiation and convective heat transfer were modelled separately, based on a number of empirical models. The accuracy of the membrane thermal model was validated against data collected on a test cell, yielding errors in the predicted membrane surface temperatures of on average 1.2°C. Errors associated with the prediction of solar radiation transmitted through the membrane skin were on average 3.5 W/m^2. Both predictions were determined to be sufficiently accurate for the generation of CFD model boundary conditions. Models of four monitored buildings were then created using a commercial CFD package. The accuracy of the simulation was validated by comparing the predicted resultant temperature with those measured at 12 points in each enclosure. It was reported that the resultant temperature prediction error was on average less than 1.5°C and always less than 4.5°C for steady-state simulations during periods when uniform internal conditions were observed in the monitored data. The accuracy of the CFD predictions was reported to decrease with the degree of stratification observed in the monitored data, which corresponded to hotter clear days. Under such circumstances, the model significantly underestimated the extent of internal stratification that was observed in the monitored enclosures. Additional simulations using more refined meshes close to the boundary surface led to the conclusion that problems associated with the prediction of internal stratification were caused by an overall underestimation of the convective heat flow between the membrane and the internal air. The coarse representation of the membrane surfaces, which due to limitations in the software had to be modelled as a series of Cartesian planes, was identified as the principal source of error in the accurate prediction of internal air distribution.

It is evident that the approach adopted by Harvie constituted a significant improvement over the previous attempts to model the thermal behaviour of membrane constructions. The emphasis of the analysis moved away from the conductive process occurring inside the membrane core and demonstrated the importance of surface heat exchanges, focussing on the dynamic radiative and convective heat transfers between the membrane skin and its environment.

Field investigations of membrane enclosed spaces

The authors' study was granted access to the membrane enclosure shown in Figs. 5 and 6, which was designed by Michael Hopkins and Partners in 1995 and operates as the central amenity building for the Inland Revenue complex in Nottingham, UK.

Figure 5. *External view looking south. Inland Revenue Amenity Building.*

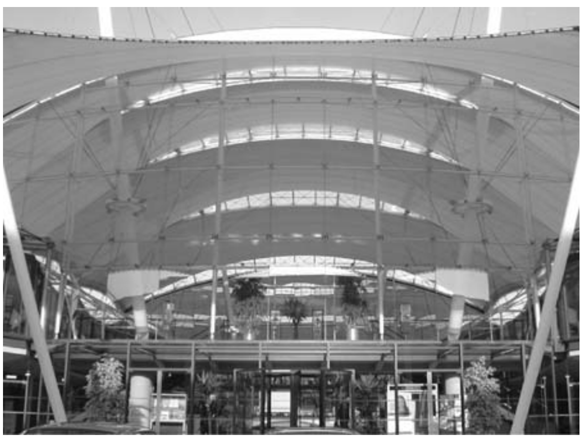

Figure 6. *South elevation, showing fabric overhang over glazed façade. Inland Revenue Amenity Building.*

A central sports area is defined by two slightly curved double-storey glazed restaurant/bar blocks enclosed by a membrane roof that covers both the central sports area and the surrounding blocks. The ends of the sports area are closed by glazed facades creating an enclosed volume of approximately 7750 m^3 with a floor area of approximately 720 m^2. The membrane roof, which comprises a single-layer of PTFE coated fibreglass, manufactured by Koch-Hightex GmbH, is supported by five glazed ladders, suspended externally from masts. The sports area is serviced by perimeter radiant heaters and louvers in the end wall allow for natural ventilation. The monitored data presented here were collected on days when the heaters were not in use and the louvers were closed.

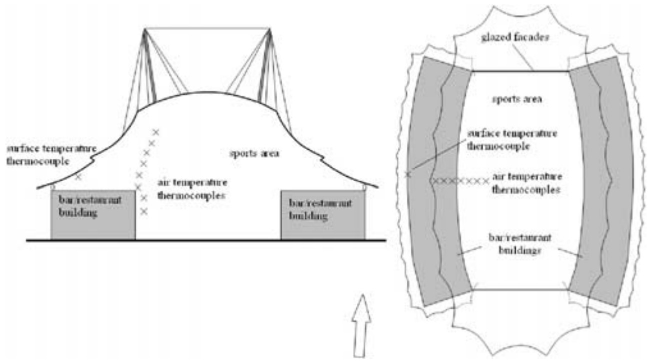

Figure 7. *Section (left) and plan (right) showing the position of the monitoring equipment in the Inland Revenue Amenity Building.*

Internal temperatures were obtained using shielded type K thermocouples suspended from the roof structure and a thermocouple fixed to the surface of the membrane using cyanoacrilate glue as indicated in Fig. 7. These were connected to a data logger set to take readings at two minute intervals.

Climatic data for global solar irradiation, dry bulb temperature, relative humidity, mean wind speed and wind direction were obtained from a monitoring station approximately 2.5 km west of the Amenity Building. The results presented, represent monitored temperature data smoothed using a moving average period of twenty minutes (ten readings). While this does not allow the exceptionally dynamic thermal behaviour of the membrane skin to be graphically represented, it greatly improves the readability of trends in this behaviour.

It was possible to identify two specific patterns in the thermal behaviour of the textile enclosure, based mainly on the clearness of the sky. During overcast days, the textile enclosures typically demonstrated a stable internal thermal environment and relatively uniform temperature distribution. Typical thermal behaviour observed under cloudy sky conditions is illustrated in Fig. 8. This behaviour was observed to be similar during both winter and summer overcast days as may be seen in Fig. 9. Technical problems encountered with a thermocouple meant that no membrane surface temperature data were recorded for the summer period.

The membrane surface maintained a stable temperature, usually close to the average between the internal and external air temperatures. As a result of the low solar gains into the enclosure and the small difference between air and membrane surface temperature, the vertical temperature stratification was very weak throughout the day and night, with an almost uniform air temperature within the space.

During clear days, large swings in the membrane surface temperature relative to surrounding air temperatures were systematically observed as indicated in Fig. 10. It may be seen that the membrane surface temperature does not appear to respond to the available direct solar radiation until shortly before noon. This is because the thermocouple was fixed to the westerly facing side of the membrane which did not

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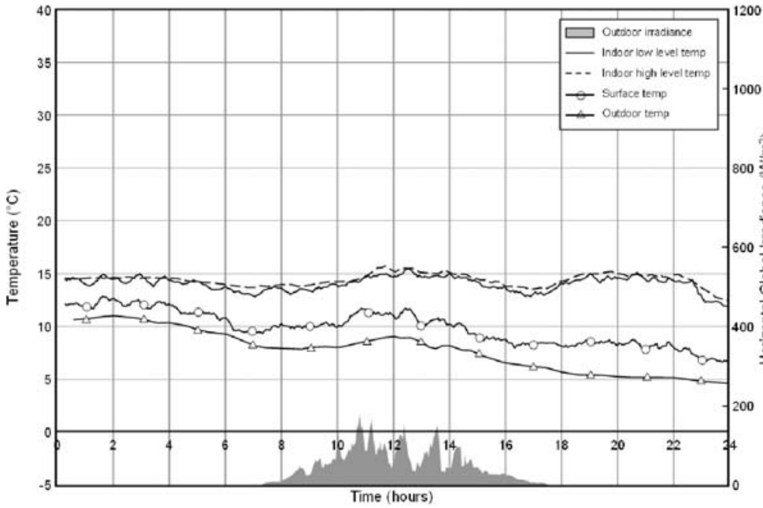

Figure 8. *Typical thermal behaviour of the Inland Revenue Amenity Building during a cold cloudy day (05/03/2003).*

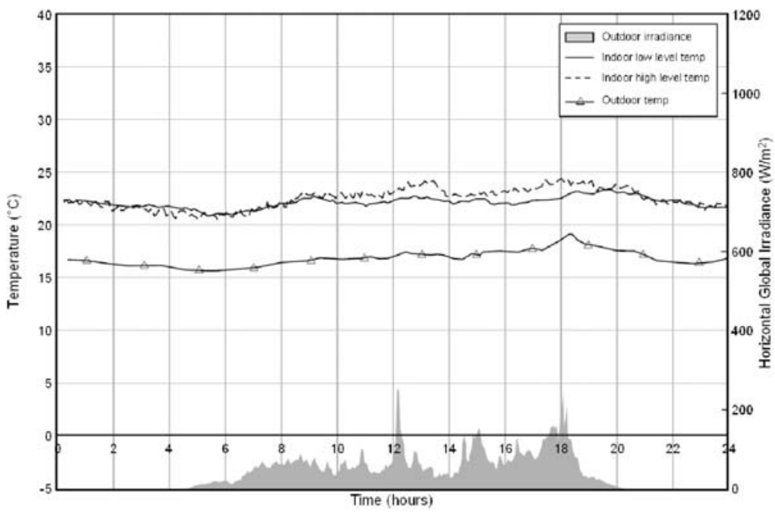

Figure 9. *Typical thermal behaviour of the Inland Revenue Amenity Building during a warm cloudy day (14/07/2002).*

come out of shade until late morning. During the periods when the monitored part of the membrane was in shade, the surface temperature dropped below the external air temperature, suggesting that long wavelength radiant exchange with the sky vault were playing an important role in the membrane heat balance.

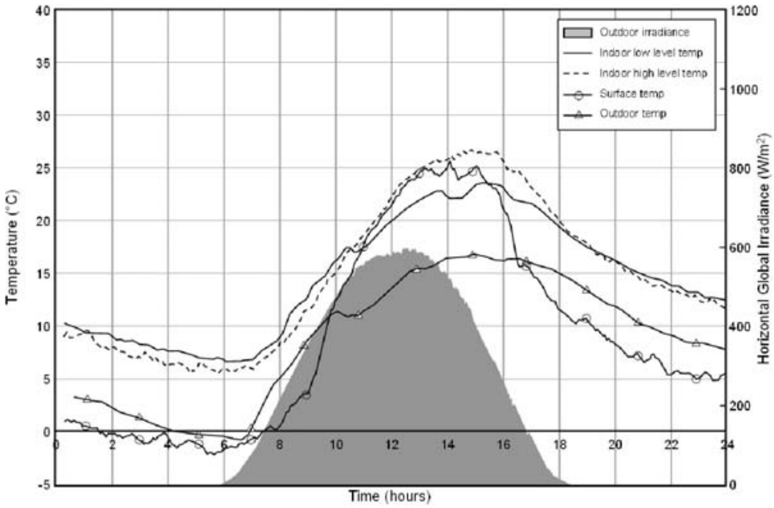

Figure 10. *Typical thermal behaviour of the Inland Revenue Amenity Building during a cold clear day (23/03/2003).*

The observed temperature difference between the occupied zone and the sensor measuring air temperature close to the top of the membrane roof indicated weak negative stratification of the internal air at night and positive stratification during the day, a pattern that follows the strong variations in the surface temperature of the membrane roof.

Recordings during the summer months revealed similar behaviour, the magnitude of the internal temperature stratifications increasing significantly with the amount of solar radiation as shown in Fig. 11.

In the case of variable cloud cover and passing clouds, the thermal behaviour of the enclosure simply oscillated between these two regimes, reacting rapidly to variations of the sky conditions.

The general patterns of behaviour observed in the present study support the observations made by previous researchers from field tests on real structures.

An updated approach for modelling the thermal behaviour of membrane structures

Developments in both the processing power of computers and the sophistication of CFD simulation tools (with, for example, the ability to construct body fitted grids) make it possible to overcome many of the barriers faced by Harvie [4] and examine again how best to tackle the problem of predicting the thermal behaviour of membrane structures.

The accuracy of CFD modelling predictions depends critically on the specification of realistic boundary conditions defining the problem to be analysed. Ill-defined input may yield substantial errors in the estimation of the thermal behaviour of an

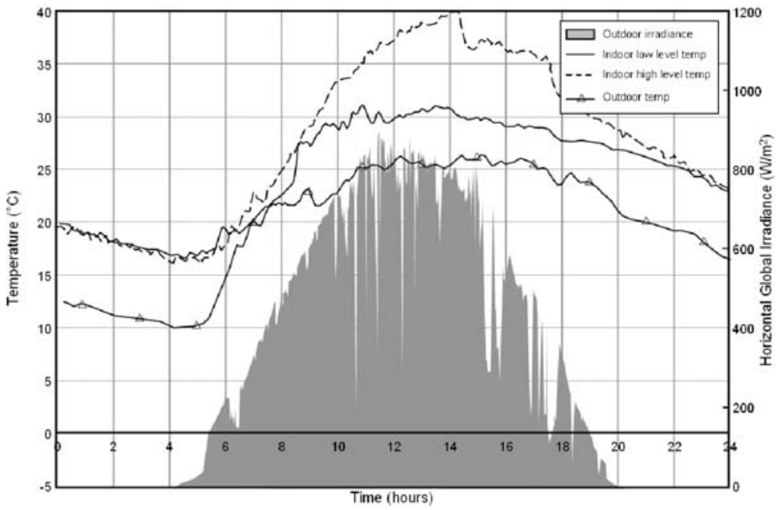

Figure 11. *Typical thermal behaviour of the Inland Revenue Amenity Building during a warm clear day (13/07/2002).*

enclosure; this inaccuracy tending to increase if the system under investigation exhibits rapid and significant change to variations in environmental conditions. It is clear therefore that any attempt to simulate a membrane structure must include an accurate model of the membrane energy exchanges. Given these are sensitive to convective exchanges, there is an implied coupling of the membrane and fluid models.

Harvie [4] suggested that the model for calculating the thermal state of the membrane structure become an integral part of a flow-modelling package, so that direct feedback could be provided to the boundary model about the air flow regime and internal air temperature in the vicinity of the considered portion of the membrane field. This suggestion is perhaps logical: after all, as the complex structural behaviour of tensile membrane called for the development of bespoke form-finding and non-linear structural analysis algorithms, it seems reasonable that a similar approach could be embraced for the analysis of their unusual climatic behaviour. Although this approach appears to be the direct answer to the generation of boundary conditions for CFD analysis, previous attempts to implement it in general building simulation have highlighted two main disadvantages [11]. The first relates to the difference of stiffness of the fluid and the solid side of the model, which can cause convergence problems created by the difference in timescale between the responsiveness of the fluid and the solid boundary. This may require the CFD code to track the two domains along different timescales. The second is more prosaic and relates to the need for rewriting a large portion of existing CFD solver codes.

It may be postulated that the first point may not *a priori* constitute a problem for the coupling of the enclosed air volume and the membrane structure, given the very low thermal mass and hence rapid thermal response of the latter. However, a rigorous analysis of the system should also include the thermally heavy weight floor structure. Coupling this slow responding thermal element to the enclosed air volume could yield convergence problems and may necessitate the use of a separate external boundary model to provide a complete definition of the domain boundary. There have been few developments attempting to address the first point, such as new algorithms to stabilise the model convergence. Nevertheless it has been concluded by Zhai et al. that '*this method was not practical for immediate use in the design context with current computer capabilities*' [11].

An alternative approach involves coupling the boundary and flow models externally, both models operating as independent simulation tools, exchanging data with each other in a predefined way. This method presents two major advantages over a purpose-built environmental analysis package:

- The use of a boundary model does not require the flow analysis code to be altered, thus allowing independent development of two numerical models.
- The boundary model can interface with virtually any flow analysis software, thus capitalising on the large range of existing well proven and benchmarked CFD packages, the port between two packages being enabled by an alteration of the interface coupling the boundary model and the package.

The suggested flow of data of the proposed model simulating the thermal behaviour of the membrane construction and the flow analysis software describing the thermal environment in the space it encloses is illustrated in Fig. 12 [12].

The model serves as a basis for the evaluation of the influence of the different energy transfer processes on the overall thermal behaviour of the membrane construction and the space it encloses. It is therefore desirable that it be constructed around a modular system of interacting algorithms, each evaluating the specific impact of these processes on the complete model. The ability to deactivate any of these calculation modules provides the means of assessing the sensitivity of the analysis to the various processes, thus assisting identifying the relevance of various modelling assumptions on its accuracy.

Conclusions

Building designers are being encouraged to reduce carbon emissions associated with maintaining occupant comfort conditions in response to consumption of finite energy resources and climate change. Tensile membrane structures have the potential to assist in this process if used appropriately, or to work against it if used without giving due regard to the conditions prevailing within the space they enclose. While the understanding gained from monitoring real structures can provide useful insight into performance, successful design is more likely to benefit from the development of effective simulation tools. This paper has outlined the characteristic features of membrane structures that such a model should account for:

- complex geometry of the membrane structure;
- time varying relationship of the membrane geometry to the sun path;

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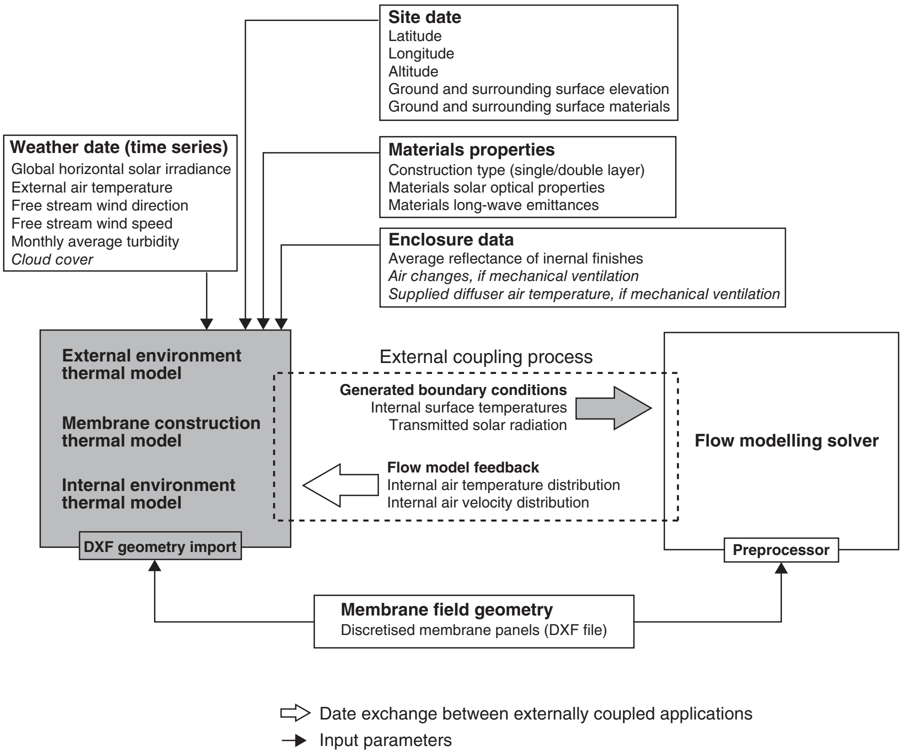

Figure 12. *Suggested data flow between the proposed membrane construction thermal model and an externally coupled airflow modelling package.*

- relationship of the membrane geometry to key internal and external surfaces and the sky vault;
- low heat capacity of the membrane and consequent sensitivity of membrane temperature to changes in its environment;
- sensitivity of both convective and radiative heat transfer mechanisms at the membrane surface to both internal and external air flows, the membrane temperature and the radiative environment;
- presence of large scale air movement and associated effects on both heat exchange and comfort conditions within the enclosed space;
- distribution of internally generated heat sources and interactions between thermally heavyweight components, such as the floor slab, solar energy transmitted through the membrane and its release into the enclosed air mass.

The model proposed in this paper builds upon the work of Harvie [4] and comprises separate modules representing the membrane, the internal and external radiative environment and the internal and external fluid environment. Developing such an approach around an existing CFD package would represent a logical approach, with the potential to minimise the need for new code development. Such a tool would allow designers to explore, in detail, the behaviour of their proposed designs in a holistic manner that accounts for the intrinsic interdependence of materials, geometry and energy sources that drive the environment within these buildings.

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