A SELECTIVE REVIEW OF THE PERFORMANCE AND MAINTENANCE ASPECTS OF FABRIC MEMBRANE STRUCTURES

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This paper was originally written in 1990 and reviews a representative selection of fabric membrane structures constructed in the Melbourne Metropolitan area between 1978 and 1988. Persons responsible for the operation and maintenance of the structures were interviewed on a systematic basis and their responses to questions covering specific performance areas are assessed. The paper provides guidance to designers on the approaches which lead to satisfactory or unsatisfactory longer term performance of fabric membranes incorporated in structures.

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INTRODUCTION

Fabric membrane structures are not a new form of construction, with many forms of air-supported and tensile structures having been developed in the early part of this century. However, it has really only been in the last two decades that improvements in membrane technology, development of methods of computer analysis and design, and a more general awareness of membranes, has meant that fabric membrane structures are now becoming accepted as a regular building component.

There are many differences, however, between fabric membrane structures and those which use more traditional building materials. One of these is the comparatively short history of membranes, leading to the relative lack of a general pool of knowledge about the short, medium and long term performance.

Steel, timber, concrete, glass, masonry, terracotta, and many other materials have been used for substantial periods of time. Their performance and their characteristics are reasonably well understood by builders and designers, and their use in most instances is also controlled by codes of practice and by detailed knowledge of their past performance in building structures.

Fabric membranes, however, are not in this position. Materials are undergoing constant and rapid development, and new uses and methods for membrane construction are being conceived and put into practice virtually every day. The materials and buildings are at the leading edge of building technology, but are also now at a stage where there are lessons to be learned from reviewing the performance and characteristics of existing membranes.

The questions which may be asked include :

- How are membranes performing from the points of view of structure, light transmission, thermal performance, maintenance, durability, and acoustic performance?
- How well are membranes satisfying the architectural concept of the designer and the expectations and the functional requirements of the user?
- How well are designers informing their clients about the durability and long term performance of the structures, and the maintenance and care required to keep them operating satisfactorily?
- Which are the aspects that are generally satisfactory, and in which areas are problems mainly occurring?

Most of the attendees at this conference have been involved with membrane structures to a greater or lesser extent over the last few years. Some would have designed or built only one or two, and some may have been involved with dozens. Yet all can learn more about the complex interplay of the different mechanisms which lead to a completely satisfactory structure.

The purpose of this paper is to contribute to the general pool of knowledge about the performance of membrane structures by examining in detail several membranes in Melbourne. In particular the authors have looked at the structures as a group rather than as individual structures, and our intention is to highlight those general characteristics of the group which stood out for positive or negative reasons. Since the performance of a single structure against a single criteria is always dependent on a unique set of factors, the examination of the performance against a common set of criteria is much more likely to lead to appropriate guidelines, lessons and comments for designers to be aware of with future structures, whatever the particular characteristics or circumstances of those structures are likely to be.

As examples of the application of the guidelines, the paper also examines in detail the performance of some individual structures against the criteria considered, and provides some specific comments of which designers should be aware.

THE STRUCTURES

The structures reviewed in the survey were:

1. St. Anne's Roman Catholic Church, Seaford, a fully enclosed church building where the roof membrane is teflon-coated fibreglass, built in 1982.

2. St. Michael's Grammar School, St. Kilda, an enclosure of a courtyard for a two-storey classroom block, the membrane being teflon-coated fibreglass, built in 1988.

3. Tintern Church of England Girls' Grammar School (CEGGS), East Ringwood, where a general purpose room abutting classrooms on two sides has a teflon-coated fibreglass roof membrane, constructed in 1985.

4. Ivanhoe Girls' Grammar School, Ivanhoe, where a PVC-coated polyester fabric formed the roof membrane to a fully enclosed art room, constructed in 1978.

5. Chadstone Shopping Centre, Chadstone, where an enclosure to the mall of a major shopping complex uses teflon-coated fibreglass, constructed in 1985.

6. Private Residence, Tarra Warra, where an internal atrium is enclosed by a teflon-coated fibreglass roof membrane, constructed in 1986.

7. St. Catherine's School, Toorak, where the Junior School Courtyard is enclosed with a teflon-coated fibreglass roof membrane, constructed in 1987.

PERFORMANCE CRITERIA

An assessment was made of each structure on the basis of eleven criteria. The table below sets out these criteria and summarises whether they were considered to be satisfied or not satisfied by the structures surveyed.

Criterion	Number of Structures Satisfying the Criterion Range 0-7
Architectural Performance	7
Structural Performance	7
Membrane Durability	7
Lighting	7
Thermal Performance	4
Ventilation	4
Acoustics	6
Cleanliness	3
Connection Detailing	4
Vandalism	6
Owners/Users Expectation	5

COMMENTS ON THE PERFORMANCE OF THE STRUCTURES

ARCHITECTURAL PERFORMANCE

Fabric membrane structures allow the expression of a wide range of architectural forms, and the use of the membrane can vary from it forming the major architectural component of the building, to it being incidental to the architecture of the building and primarily used for one of its properties such as translucency or the ability to achieve long clear spans.

In all of the structures reviewed the architectural aspects were considered to be satisfied. A general statement is that membrane structures allow imaginative architectural solutions, but as with any other building form or material, an inappropriate architectural approach will always be unsatisfactory.

Architects and designers not familiar with membranes should thoroughly acquaint themselves with existing buildings and available materials, and work with specialist designers so that the architectural requirements are met concurrently with the provision of satisfactory performance in all other areas.

STRUCTURAL PERFORMANCE

The structural performance of the membranes was not an issue in the structures reviewed, for all performed satisfactorily. Of course the membrane designer must consider all the loads and loading conditions appropriate and adopt adequate factors of safety.

At this stage there is a substantial body of knowledge available, and the authors believe steps now need to be taken in Australia to codify the more important design rules and approaches to ensure that the record to date for the generally satisfactory structural performance of membrane structures is maintained.

Deflection of some of the membranes under wind load was reported. These deflections were within the design parameters and were not regarded as a problem by the users of the building.

Similarly, no structural problems were reported with the structure supporting the membranes, although care should be taken where the membrane boundary condition is a flexural member attached to or trimming a rigid component such as a masonry wall. In this case, compatibility of deflection must be considered at the design stage. Membrane tensions introduce significant loads into the supports, and the deflection of flexural boundary elements needs careful consideration.

MEMBRANE DURABILITY

No problems were observed with the durability of the membranes on the structures reviewed. Although the majority were of teflon-coated fibreglass, the oldest utilised a PVC-coated polyester fabric which was still performing satisfactorily after 11 years.

Where some problems of durability have occurred at some areas of the structure, these have included:

- bonding of flaps or sealing cushions to the membrane, where a satisfactory join between the membrane and a rigid component of the structure was not able to be maintained.
- protection systems for structural steel, where either site application of the top coat, or touching up of damage has not been carried out as specified, or where holes drilled for membrane installation purposes have not been later sealed, and moisture penetration has caused rust.

LIGHTING

One of the more important properties of membranes is their translucency. As all the structures were in regular commercial, institutional, or private use, the membranes were all white and coloration within the buildings was not a problem.

All of the users reported acceptable to high levels of satisfaction with the lighting. The following specific comments could be considered by designers:

- Good lighting often means poor thermal performance (refer to later comments).
- Daylighting was always adequate, and night lighting, especially with indirect lighting reflected from the underside of the membrane, was also satisfactory in all structures. However, lighting from beneath at night does highlight any lack of cleanliness of the membrane.
- Where visual presentations such as slides, etc. are required, their use is severely restricted during the day.
- Variations in lighting achieved by selective use of liners can be effective. For example at St. Anne's Church the liner stops short of the apex of the roof to allow increased translucency to highlight the sanctuary.

THERMAL PERFORMANCE

Thermal performance was one of the most widely variable characteristics of the structures reviewed.

Three of the seven users reported a high level of satisfaction with the thermal performance. These three structures all had in common either extremely good cross ventilation or cross ventilation combined with substantial mechanical air extraction from the apex.

One other facility was reported to have satisfactory thermal performance, where the membrane forms a relatively minor component of a large commercial facility with good air-conditioning.

Three users reported thermal performance as a major problem, with high summer temperatures creating uncomfortable conditions. Cold winter temperatures were also a problem with the larger structures. Even when heating systems were available, operating costs, lead times to bring temperatures up to comfort levels, or lack of flexibility in the heating system meant that comfortable temperatures could still not always be achieved.

Designers must address thermal performance at the earliest stages, through the use of sensible orientation and shading, liners and insulation, natural and mechanical ventilation, and air-conditioning systems.

Usage is also important, as a space used for relatively short periods of time can be satisfactory with temperature variations which would not be acceptable in a classroom or meeting room.

VENTILATION

Adequate exhaust ventilation or cross ventilation is linked to the thermal performance, especially in preventing temperatures rising to uncomfortable levels.

At St. Michael's Grammar School and at St. Catherine's Junior School, the membranes partially enclose courtyards, and there are clear openings of about one metre between the main building roofs and the lower edge of the membranes. Combined with good cross ventilation at lower levels and the fact that the courtyards are not regarded as closed indoor spaces, users report a high level of satisfaction, with conditions warmer in winter and cooler in summer than for the previous unenclosed courtyards.

For the enclosed spaces, substantial forced exhaust of hot air from an apex point was necessary for satisfactory thermal performance. Even for buildings with natural ventilation at the apex, air movement and temperature control were still regarded as unsatisfactory.

It should be noted that condensation on the underside of a single layer membrane can be significant, especially in colder areas and where indoor gardens are regularly watered, keeping humidity high. Ventilation needs to be extremely good in these situations.

ACOUSTICS

Acoustics were not a major concern, with most users reporting satisfactory levels of noise and reverberation control. The only problems reported were occasional disturbances during periods of heavy rain, and some reverberation and movement in the membrane when doors were shut quickly in the enclosed space.

However, for busy or noisy uses, designers should pay specific attention to the influence of membrane shape on acoustic performance. Specific measures of acoustic control are required in many structures such as air-supported cable restrained domes.

CLEANLINESS

Keeping the fabric membrane structures clean was a significant concern to most of the users. The only three reporting satisfaction in this area either:

- had initiated a regular maintenance program, or
- had only twelve months or two years operation of the building, and regarded the space beneath the membrane as an external space, where cleanliness was of less importance than it would be inside a building.

Cleanliness has several aspects, and is more important for fabric structures than for many conventional strictures because:

- the excellent lighting highlights dust, cobwebs, etc., which would not be as noticeable with a non-translucent roof.
- the translucency of the membranes means contamination is obvious whether it is on the inside or the outside.
- many membrane structures have a complex or unusual support structure with surfaces and recesses which hold dust, attract spiders, etc.
- lack of cleanliness is highlighted because the membrane provides a focus to draw the users attention to where the cleanliness problem is.
- access to the external and internal surfaces is often difficult and sometimes impossible.

Designers must consider the problem of keeping the structure and membrane clean, right from the outset. This includes making provision for adequate access to the external and internal surfaces of the membrane. All structures should have a regular maintenance and cleaning program set up to control cleanliness before it becomes an unsatisfactory aspect.

CONNECTION DETAILING

This obviously varies between structures, and many aspects of connection and support details are inter-related with architectural appearance, structural performance, and durability.

Generally an acceptable level of satisfaction was found, although designers should note that durability of connectors is of paramount importance. Consideration should be made of the environment, appearance, accessibility and function of the connection, and the required life and use of he structure, so that an appropriate choice of materials is made. Preferred materials include stainless steel, galvanised steel, or other non-corrodible metals or plastics.

VANDALISM

Membrane structures by their very nature attract attention, and some of this attention may be unwelcome. The fabric membrane is also more easily damaged than many conventional building materials, and repairs and patches are difficult to conceal.

For these reasons it is essential that designers are aware of many factors about their structures, and consider the possibility if vandalism and malicious damage at the earliest stage of the design.

Only one of the structures covered in this survey, St. Anne's Church, had suffered from vandalism. Some areas of the fabric are about 2.4 metres from the surrounding pavement, and readily accessible from the lower supporting masts. Holes had been punctured in the fabric at various places near these low points. Repairs had been carried out by heat welding patches over the cuts, but these are quite noticeable. The Church was at the time of the survey considering a proposal to completely renew the damaged sections and provide some form of barrier below to reduce the ready access to the fabric. Since the vandalism, external floodlighting has been installed, and unfortunately, barbed wire has had to be installed around the lower column heads. This detracts from the otherwise simple lines of the support system.

Points for designers to consider are:

- whether passive or active security systems will be in place
- ease of access to the membrane. Often the membrane is a roof and has conventional walls restricting access to it. However, if the membrane comes close to the ground, consideration should be given to measures such as providing dense, spiky vegetation, water moats, or other features to make access difficult. Obviously it is best to integrate these into the initial design rather than add protective measures at a later stage.
- use of the building. If the building is generally in use and occupied for most of the time, then different measures may be appropriate than if the building is occupied only on a periodic basis.
- lighting can be used to reduce vandalism.
- location of the membrane. Highly visible membranes may be less subject to vandalism than ones where damage can occur unobserved.

OWNER/USER EXPECTATIONS

Throughout the authors' discussions with building owners, it was apparent that where there were disappointments in relation to the fabric roof, many of these stemmed from false expectations of its performance. Owners need to be fully advised in the early design stages of the limitations of the fabric membrane, just as they are advised of the benefits. Four of the seven owners felt their expectations were met, whilst three felt that their membrane structure did not perform as well as had been expected.

One of the most beneficial architectural qualities of the membranes is their translucency. However this flooding of daylight emphasises, for example, the general state of cleanliness of the building. It is therefore necessary to stress the need for an ongoing cleaning/maintenance program. This program would generally require a greater input than that which should be carried out for any building if a respectable appearance is to be maintained.

The thermal performance and ventilation of the structures was the other area where a significant number of users experienced disappointment with their structure. These areas require detailed attention from the designer, as discussed elsewhere in this paper.

CONCLUSIONS

The conclusions to be drawn from the investigations described in this paper are:

1. All fabric membrane structures require a repair and maintenance schedule to be prepared by the designer so owners are aware of the actions that need to be taken to ensure a high level of satisfaction with their structure. This schedule should include;

   - periodic inspections by the designer and contractor (at least annually).
   - a regular cleaning program, with a description of the methods and materials to be used.
   - repair procedures for emergency use.

2. For cleaning, designers must consider the provision of access to the external and internal surfaces of the membrane. Whether cleaning is to be carried out by installation of scaffold, cherry pickers, or by other means must be considered at the design stage.

3. Thermal performance and ventilation must be considered in detail at the design stage. To achieve satisfactory temperature levels, especially in summer, it is essential that good cross ventilation and forced extraction of air from an apex point is provided.

   Satisfactory winter performance, especially in the evenings requires a heating system which is capable of a short response time, can cope with the heat loss through the membrane, and can be directed or zoned to those parts of the structure being used at a given time.

4. Durability of membrane structures appears to be good to excellent. From the structures observed, an expected life in the order of at least 15 years for PVC-coated polyester, and longer for teflon-coated fibreglass, can be confidently expected for Melbourne climatic conditions. Newer fabrics are also further increasing the expected life. Care should be taken with coloured fabrics, which are more likely to fade than white fabrics.

5. Clients and owners of buildings with fabric membranes must be fully informed of all the positive and negative aspects of membranes right from the outset. Only in this way can the overall levels of users satisfaction be raised, and their expectations met.

ACKNOWLEDGMENTS

Space precludes listing all the people who spared the time to be interviewed about the performance of their structure, but the authors' thanks are extended to all those who assisted. It is the authors' intention to assist those users who reported problems to find solutions to increase their satisfaction with their membrane structure, and to carry out follow-up investigation to continue to monitor the performance of these structures.

REFERENCES

A more detailed presentation of the data used to prepare this paper is contained in the final year project report entitled;

"An Investigation of the Long-Term Performance Characteristics of Membrane Structures"
by Jeff Uren and Sam Verrocchi

Building Engineering Degree course at Footscray Institute of Technology.

Copies of this report are available to interested persons from Chis Tattersall at the Department of Civil and Building Engineering, Victoria University of Technology,
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