MEMBRANE STRUCTURES FOR COMMUNITY FACILITIES

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This paper reviews the author's recent experiences with the application of membrane structures for community facilities, particularly for local government. Discussion is presented on the applications, materials, methods of procurement, and design details.

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INTRODUCTION

Membrane structures in Australia have been used for all types of applications. There are membrane structures which comprise a complete building, membrane structures which provide a roof to a conventional building, and membrane structures which are ancillary to conventional buildings , or are independent structures in their own right.

These structures have been constructed for a wide range of uses, including retail, religious, educational, residential, tourism, hotels and entertainment venues, sporting, advertising and promotion.

During the decade of the 80's, and particularly the latter part of this decade, the level of construction activity in Australia was high, and membrane structures seemed to have the potential to be used for larger and higher profile projects than ever before. New materials, providing longer life and reduced maintenance for a lower cost, were becoming available and gradually being incorporated into structures in all areas of Australia. The incorporation of membrane structures into major sporting facilities, major shopping complexes, and high profile tourism facilities, seemed to assure the future of the industry.

With the slowdown in economic activity which we have experienced in the 90's, the number of large, high-profile projects has decreased significantly, and the potential for the incorporation of membrane structures into such projects has also decreased. Does this spell disaster for the industry, or are there other areas of the market which can be tapped? This is one of the questions this paper addresses.

If membrane structures are to be used in smaller, less glamorous applications, do the designers and contractors need to take different approaches? Is there scope for a significant number of smaller structures, and can these provide a sufficient volume of work to support the industry in these hard times, and better equip us for the future? The author certainly believes so, and this paper examines only one of a number of avenues of opportunity. This particular avenue is the application of membrane structures in the provision of local community facilities, typically constructed and managed by local municipalities.

There is a huge range of applications for membrane structures in this area, and the author has seen a number of these on the drawing boards or actually having been provided. A number have been successful, yet there are also pitfalls for the unwary, and lessons to be learned. As we proceed through this paper, we will review these applications, and some of the special characteristics in the design of these structures which should lead to a greater amount of acceptance from the community and those local government officers who are charged with the procurement of these facilities.

COMMUNITY APPLICATIONS

There are a number of different types of applications of membrane structures, through local government, for which membrane structures are well suited and have been used.

In the area of larger structures, these include

- air-supported structures for swimming pools and sports facilities
- tensioned membrane structures at council owned retail facilities
- tensioned membrane structures at football grandstands
- sound shells and entertainment venues, whether mobile or fixed,
- tourist facilities.

When smaller structures are considered, the range of applications becomes even broader, and applications which have or could be used include

- shade structures over swimming pools, particular wading pools where small children are in shallow water
- shade structures beside swimming pools
- shade and weather protection structures at playgrounds, kindergartens, chid care centres, etc.
- weather protection structures at sporting facilities (tennis courts, volleyball courts, netball courts etc.)

INITIATION AND DEVELOPMENT OF PROJECTS

With local government in Victoria, the road from the initial expression of a need by the community, to the completion of a project, can certainly be a long and winding one. A typical small to medium sized project (say with value above $50,000) may pass through a number of stages such as the following:-

- initial identification of the need by a user group or facility operator,
- a review of the needs by a council officer,
- a recommendation at council officer level that the project be further investigated, feasibilities be examined, and a budget be established.

In many instances where there is a significant building component involved with the project, an architect is usually engaged to develop proposals and budgets. An important factor in the promotion of the use of membrane structures is an awareness amongst council officers (usually engineers) of the appropriateness and application of membrane structures in particular instances. Where this awareness exists, hopefully having been developed by promotion by the MSAA and its members, and the council officer has an appreciation of membrane structures, then it may be accepted that their design is best done by consultants with specialist skills and experience, preferably members of the MSAA. These consultants may be engineers, contractors, or architects, but they must have a wide knowledge of forms, materials, design parameters, and support and restraint conditions. In these instances, the steps which may then occur in the development of the project are often as follows:-

- engagement of a specialist consultant in membrane structures to prepare a feasibility study examining the issues and constraints, suggesting some structural forms which would be suitable, and establishing a budget.

- the report and budget would be put to a council meeting with a request that further development of the project to a stage where public comment and user group input can be obtained, and where the budget can be refined. This stage may involve the consultant presenting information on the proposal to groups of councillors at sub-committee meetings or full council meetings. If approval is obtained, there would be a source of funding identified, and the project may be further developed.

- Once the project is further developed, and input has been obtained from all interested parties, the documents would be used for any necessary planning permit application, and further public comment would be sought.

- Presuming a planning permit is obtained, documents would be prepared for building permit, and tender. Depending on the size of the project and the policies of the particular council, tenders may be open tender, selected tender, or even be broken into separate packages to be project managed by the consultant. Our recommendation to council would always be that only those contractors with demonstrated experience in fabric structures be considered. If there is a policy of open tender, this may be able to be satisfied by calling for open registration of interest, and selecting tenderers only from those than able to demonstrate appropriate skills and experience.

PNEUMATIC OR TENSIONED MEMBRANES?

One of the obvious areas of difference between types of membrane structures is whether pneumatic or tensioned membrane structures are used.

Before the merits and otherwise of these two alternatives are considered, it may be worthwhile to define exactly what is meant by each of these descriptions.

Pneumatic Structures.

Pneumatic structures actually consist of two subsets, which can be classified as air supported structures and air-inflated structures. Air-supported structures are generally classed as those structures where the membrane encloses the useable space of a building, and the membrane is supported by keeping this interior useable space at a slightly higher pressure than the exterior. Air-inflated structures, on the other hand, utilise a closed membrane form (such as a tube or pillow), to form a relatively rigid element which is used as a component of the building. Air-inflated structures may be combined with sections of tensioned or non-tensioned membrane to form the complete building.

The common factor with both air-supported and air-inflated structures is that they both require an enclosed space to be maintained at a higher than ambient pressure in order to provide their stability and structural integrity. This means that inflation systems have to be provided, and also means that these inflation systems must be suitably reliable and have an appropriate amount of redundancy to ensure that structural integrity is maintained. If the inflation systems fail, the structure collapses. The pressure difference in air-supported structures may range from 150 to 500 Pascal (15 to 50 mm of water), whereas in air-inflated structures it is typically higher. Air-supported structures are more commonly used than air-inflated structures for building s because of the difficulty of maintaining inflation of elements at higher pressures, and the fact that the collapse of an air-inflated structure due to loss of pressure can be quite sudden, whereas with an air-supported structure it is usually relatively gradual.

The major difference between air-supported and air-inflated structures is that with an air-supported structure, the useable interior space of the building is maintained at the higher pressure, whereas with the air-inflated structure, an enclosed element which does not include the useable interior space is kept at the higher pressure.

This means that for air-supported structures there is a requirement for entrances and exits to be so detailed that the loss of air through these is controlled. This requires some form of air-lock, and the most common method is to use revolving doors.

The major advantages of air-supported structures are that

- there is minimal structure (being basically the membrane and the restraint system), and hence the capital cost, even allowing for the inflation system, is relatively low, and
- they are relatively easy to erect and take down,

when compared to a conventional structure.

The major disadvantages are that

- the inflation system must not fail, or the structure will deflate, with a high risk of damage or loss, and
- the lower capital cost is offset by higher running costs, and for some applications the specific properties of air-supported membrane structures mean that these running costs are considerably higher.

Tensioned membrane structures.

Tensioned membrane structures achieve their stability and structural integrity from the combination of a prestressed (tensioned) membrane acting against restraints provided by a variety of elements. These can be rigid frames, tensioned members such as cables and points of restraint created using masts, guys, and anchor points. For the membrane surface to be stable, it must be developed so that at any location on the surface, it is curved in two directions, and the tensions acting in each of these two directions resist each other to form an equilibrium condition.

The advantages of tensioned membrane structures when compared with conventional structures are many, but more specifically in relation to air-supported structures, the main advantages are that

- once they are erected and tensioned, they are stable structures in their own right, without needing a continual inflation system, and
- a much wider range of membrane shapes is available because the surfaces are curved in two directions , and these curvatures are of opposing sign.

The disadvantages include that

- capital cost is usually higher, especially if there are rigid frames as boundary conditions, rather than catenary edge cables and masts, and
- unless a lot of care is taken with detailing, and usually so even than, erection and dismantling are more involved, and they are not as suitable for structures which are to be erected and dismantled often.

THE PRACTICAL USE OF AIR-SUPPORTED STRUCTURES

There are a number of examples of air-supported structures which have been used for community facilities in Australia. Some of these, such as the North Sydney Pool, and the Lillydale Centenary Swimming Centre in Victoria, have been providing satisfactory service to their owners and the public for a number of years. Other examples have not been as successful, and a number of air-supported domes have been lost as a result of failure of the inflation systems, and deliberate or accidental damage.

The major points to consider with the design of any air-supported structure include the inflation system and its controls, the entrance and egress provisions, the arrangements for erecting and taking down the structure, and the supervision and monitoring of the operation of the facility. Taking these in order, the following comments are made:-

The inflation system and its controls

- the inflation system needs at least two independent units (fans and motors), so that at least one is available in times of breakdown or items being taken out of service for maintenance. If maintenance requirements mean that one unit will be out of service for significant periods (more than a few hours), then probably two more units are necessary to cater for mechanical failure of one unit whilst the other is being maintained.
- The power supply to the fans and motors will usually be from a supply authority grid, but to allow for disruption to supply, a backup generator should always be provided. The backup generator is usually powered by a diesel motor. It should be tested at least on a weekly basis, and suitable provisions for maintenance should be made. Fuel levels should be checked regularly to ensure the generator does not run out at a crucial time.
- The control system should provide for the backup generator to automatically start and provide power to the fans if the mains supply is interrupted. Once this occurs there should be an alarm to indicate that supply has been cut, and to advise the operator to switch back to the mains supply when it becomes available. Preferably this would be an automatic feature in the control system.
- The switchboard supplying power to the inflation system should be designed in separate sections, one for each of the inflation units. This is so that one section can be isolated for maintenance, alterations or repairs, without disrupting supply to the other units.
- Fans should be able to run at variable speed or with variable pitch to the blades for control of supply air for inflation. The control system for the fans should take account of a number of factors including internal air pressure, internal air temperature, and external wind speed. There should be a minimum of components such as belt drives etc. which wear and have to be replaced on a regular basis to guard against breakage at inconvenient times.

Provisions for access to and egress from the structure.

- The number and type of access and egress points will depend on the use of the facility.. The most usual method for the main entry/exit point or points is to use a revolving door, and this provides reasonable capacity for most uses. Emergency exits can be single doors with no airlock, as they are not intended to be used often.

- Where there are plant or service areas adjacent and with access to the pressurised area, these may cause problems. If these ancillary areas are not intended to be pressurised, then they act as a defacto air lock between the pressurised interior and the exterior. They can be subject to high pressures on the doors prior to pressures being stabilised. At a pressure differential of 300 Pa, the force on a standard door can be as high as 0.50 kN, (the force required to lift a mass of 50 Kg). This may require particular attention to be given to the construction of the door, and to the hinges and door hardware used. Doors into the main structure, and secondary doors into plant or storage areas can be shut violently by differences in pressures. This also needs consideration when selecting types of doors, door closers, etc.

Arrangements for erecting and removing the structure

One of the advantages mentioned for air-supported structures is the relative ease of erection and disassembly of the structures. There is no frame to erect, the membrane merely needs to be arranged over the area in which it is to be erected, fixed down around the edges, and the inflation system turned on. There are a few points to consider which can make this process more or less difficult , and some of these are:-

- Holding down details around the edges of the membrane, and connection points at sides of doors, etc. need to be detailed for easy and repeated connection and disconnection. Bolted connections can be time-consuming, and should be minimised. Where bolted connections are used, there should be clear access for tools, and it should be remembered that even galvanised bolts are likely to suffer surface damage after repeated installations and will be likely to corrode.

- The membrane needs to be able to be handled in reasonably sized sections, and for larger applications this will require mechanical splices. These again should be detailed for ease of access for tools, and particular attention should be paid to the materials used, to avoid corrosion. Air-supported structures are often subject to limited budgets, but owners should be made aware of the potential problems of trying to save on materials used for connector plates and bolts.

- The membrane can be easily damaged or made dirty. Footprints on the membrane when it is on the ground do not always clean off and all care should be taken to avoid walking on the membrane or marking or making it dirty. Where the membrane is to be laid out, protective plastic sheeting should be installed beneath it, and of course the membrane should never be taken down and put into storage unless it is completely clean and dry.

- Within the space enclosed by the membrane, all components such as lights, seats, air inlet registers, etc. need to be detailed so that they can be removed prior to taking down the structure. One excellent method for ease of inflation is to have the pressurisation air ducted underground to come up through horizontal openings in the surface to be enclosed. This means for installation the membrane can be laid flat over the floor or surface, and connections of inlet ducts do not need to be made prior to inflation. Once the membrane is erected, additional ducting can be installed to raise the level of the inlet air to a suitable height, if it is being directed in at only a few locations.

Supervision and Monitoring of the Operation of the Facility.

Air-supported structures, as mentioned previously, require continuous operation of the inflation systems to remain erect and stable. Many factors can contribute to or cause deflations. These include plant failure, interruptions to the power supply, accidental damage or acts such as leaving emergency exit doors open, vandalism, and extreme weather conditions. Air-supported structures require continual attention and monitoring to prevent these occurrences or provide a quick and appropriate response if they do occur. This means that a person with reasonable knowledge of the facility has to be in attendance or available at all times, twenty-four hours a day, three hundred and sixty-five days a year. There are myriad areas where problems may arise, and even the best-designed control system may not be able to cope with them all. In many cases deflations or partial deflations can occur without major damage, but if deflation occurs in conjunction with other factors such as windy conditions, it is quite likely the membrane will be damaged, by tearing due to flapping, by tearing over objects beneath the canopy or to other reasons. Depending on the cause, deflations can occur over periods of several hours to less than one hour. Considerations for operators include:-

- Protection against vandalism or unauthorised use. Preferably the structure should be protected with suitable fencing and be well lit, as well as being regularly patrolled during hours when no-one is in attendance.

- A detailed and readily understood operations manual is essential both for day-to-day operation and maintenance and emergency repairs. This manual should not be just a collection of technical details on the various items of plant, but also include an overview of the control systems and how the whole system is intended to operate, as well as a list of suitable contractors and consultants who can immediately advise and act if problems arise.

- Permanent staff who operate and maintain the facility and become familiar with the behaviour of the structure and the plant.

Special Considerations for Air-Supported Structures over Swimming Pools.

A common use of air-supported structures is for swimming pool enclosures, particularly for municipal pools. With municipal swimming centres becoming more popular, the use of an air-supported structure can provide an enclosed facility for all-year-round use at a much lower capital cost than a conventional structure. Actual costs vary depending on facilities, but a typical installation we have reviewed obtained an enclosure for an Olympic sized pool for around $1.0 million, compared an estimate of $4.0 million for a similar facility using conventional construction.

This capital cost difference means that in some instances a facility can be made available where there is not funding available for a conventional type of construction. There are, however, other matters which need to be considered in conjunction with this lower capital cost when developing a proposal for the use of an air-supported structure for a swimming pool. Apart from the general considerations necessary with the use of any air-supported structure, matters specific to swimming pool facilities include:-

- With the warm, humid atmosphere, usually with high levels of chlorine, corrosion of metals proceeds at a rapid rate. All materials used need to be chosen or treated to be compatible and to have minimum potential for corrosion. Even stainless steel can corrode under the conditions which are present in a swimming pool building. Electrical components and mechanical plant, even though usually located in a separate room to the main pool area, are also subject to a much higher level of corrosion than would normally be the case.

- Similarly to the above, the conditions lead to more rapid deterioration of timber, and any timber components, especially doors and joinery, need to be selected for maximum durability and dimensional stability under humid conditions, as well as the strength to withstand treatment arising from the potential differential pressures.

- Operating costs can be very high.

  Firstly, there is the need to keep the structure inflated, which requires the fans to be running continually. In a conventional structure, ventilation systems are needed when the facility is in use, but these can be turned off when the facility is closed.

  Secondly, to obtain optimum usage and income, indoor swimming facilities are not only used for recreational swimming and training, but for organised activities including lessons, aqua-aerobics, etc. The temperature of the water for these activities is usually required to be about 31^{o} to $32\ ^{o}C$. To keep misting to an acceptable level, the air temperature is usually kept 1^{o} to 2^{o} C above the water temperature. Combined with the requirement to provide a reasonable number of air changes (usually at least 6 per hour), and the enclosed volume, this requires a lot of energy for the heating of the air. Since this air becomes very humid, it cannot be recycled, and is discharged to atmosphere. Thus the energy costs of the facility are not only related to the heating of water, but to the heating of the air as well. These energy costs are required to some extent by conventional buildings as well, but the relatively poor insulation of the air-structure, and the requirement for air for inflation as well as ventilation, mean that energy costs are higher than for a conventional facility.

- Another point to consider is whether or not the structure is to left in place permanently or be removed during, say the summer months. If the structure is left up during the summer months, there are still significant energy costs associated with heating the air and keeping the structure inflated, and there are, surprisingly, additional costs associated with heating the water because of the solar gain which is lost by having the water shaded. The actual cost of taking the structure down and putting it up can be significant ($8,000 to $10,000 advised as the cost for one structure), and in addition there can be disruption to and loss of income from regular activities such as coaching and exercise classes during the period the structure and all the necessary internal components are being erected or taken down.

- Along with the above, since the membrane needs to be dry and clean when it is put away, the pool needs to be drained during the process.

TENSIONED MEMBRANES

The use of tensioned membranes for various applications for local government and private community facilities is attracting a significant amount of interest at the present time. The applications include shade structures at swimming pools, protected outdoor play areas for children, weather protection canopies for spectators at sporting grounds, and enclosures or protective structures for sporting activities such as tennis, netball, and volleyball. The applications are generally all characterised by having a low budget, and so the time and effort involved in the design, and the details and materials adopted, are all restricted.

Where a tensioned membrane is considered to be an appropriate solution, as opposed to a pneumatic structure, there are a number of design considerations which need to be taken into account in the development of the design. The structural considerations, such as wind loading, member forces, and hold-down are obvious, but other considerations include:-

- type of material. Is an impervious or pervious material to be used? Obviously if the structure is intended to provide weather protection to play areas for children then it would have to be impervious, but if it only to be a shade structure over a pool or play area than perhaps a pervious fabric such as shadecloth would be suitable. The type of material used has an input into the size of the structure, whether secondary supports are required, what shapes can be achieved, the cost, membrane drainage, and many other matters.

- membrane shape and type of support system. Typical applications are required to achieve maximum result in terms of area protected, for minimum cost. Sophisticated or extensive steel support systems may be able to be afforded, but usually are not. Common membrane shapes are hyperbolic paraboloids (hypars), either single or joined.

- access around the structure, and use of the area. Guyed masts supporting catenary edge cable are probably one of the cheapest support systems, but where room for the guys is restricted, or where guys would interfere with access, struts between the top of posts may have to be used. These can be satisfactory if spans are not too large, although deflection under self weight needs to be carefully considered.

- drainage of rainwater from the membrane. If a pervious membrane such as shadecloth is used this is not a problem, but if an impervious material is used, the membrane shape will tend to concentrate rainwater at specific areas. Some shapes control discharge better than others, but hypars with catenary edge cables will tend to direct runoff over a section of the perimeter.

  Around a swimming pool, there is usually drainage on the concourse, and the design should consider the drainage points and try to direct rainwater to areas where it can enter stormwater drains without causing further problems. When rain is falling there will be areas where people walking around the structure would be likely to be wetted by the discharge, but around a pool and in the rain this seems not to be a big problem. It is preferable that the roof discharge not be directed back into the pool, as the cover will pick up an accumulation of dirt between periods of rain, and this would enter the pool as a concentrated discharge, which would cause temporary discolouration and possibly unhygienic conditions until the filtration system can remove the impurities.

  For a cover to a play area, rainwater discharge needs to be more carefully controlled, and new drainage may well have to be provided. Where possible designers should consider oversailing the membrane over an existing roof to provide one area of guaranteed dry access to the area under the structure.

- Vandalism or Malicious Treatment. Where the structures will be used by children, they should be designed so that the children cannot easily climb the guys or masts or get access onto the structure (ie latticed tower supports would not be suitable). Cables and guys which are accessible from the ground should be designed so that children swinging on them or pulling on them will not create excessive deflections or vibrations in the structure. This is one reason that a strutted frame may be preferred.

  Of course, whether the structure is used by children or adults, vandalism is always a concern, and unsupervised access to the structure should be avoided. Certainly, the most vulnerable component, the membrane, should not be within reach from the ground or nearby objects, or it is almost certain to be damaged at some stage.

CONCERNS WITH THE PROCUREMENT PROCESS FOR SMALLER STRUCTURES

The author believes there is a significant market for smaller membrane structures for community use, but the amount of work which may have to be put into the development and approval of the project, added to the work in actually designing and detailing the structure, means that design costs are high. This becomes a real problem when the construction cost of the project may be very low, as the design costs form a very significant percentage of the project cost.

On some municipal projects, the membrane structure can be a small component of a larger project, and may not receive as much attention as it deserves. Designers without a great deal of experience underestimate or do not even realise the need for elegance and the application of basic principles of membrane structure design. Thus the danger is that issues of providing for movement at supports, concentric flow of forces, adequate membrane restraint, minimisation of wear, deflection of supports, etc. are not properly addressed. An inexpensive structure where these issues are not properly considered is not going to be well received by the owner. This highlights even more the need to have experienced designers involved, so that maximum design efficiency is achieved.

Other factors which will improve the relationship between design costs and project costs include:-

- the use of the same basic structure in several locations. There are still some design costs associated with each location, and there are variations in soil conditions and footing details, wind loading etc. There will, however be economies in design and fabrication if there are several of the one type of structure included in one project.
- further development of modular and standard structures. With the use of similar structures, obviously the situation will develop where designers and fabricators can offer a number of "off the shelf" structures, and there are obvious cost efficiencies in this.
- improvements in computer-aided design facilities
- improvements in computer aided manufacturing where cutting of fabric panels is done using computer controlled machinery working directly from the design or patterning software.

SUMMARY AND CONCLUSIONS

Membrane structures, both pneumatic and tensioned membrane structures, do, I believe, have many applications in the local government, municipal and community area. The nature of the procurement process and the projects themselves do introduce some special problems. The projects tend to be small and with low budgets, and the overall costs for management and design are a significant proportion of the total project costs.

Like any other membrane structure, there is still the need for discipline and experience to be applied by the design team. Hopefully as the number of applications grow, the ability to re-use designs and details will continue. Some of the points raised in this paper outline considerations for specific types of structure and specific applications which are important to designers and to the owners and operators of community facilities.

The need for experience and knowledge of materials, membrane forms, design considerations and appropriate details is not diminished by the fact that some of the structures, eg shade structures for swimming pools or playgrounds, are small and relatively simple.

The MSAA and all its members needs to do all in our power to educate and advise those responsible for the procurement of community facilities, so that they realise the facilities membrane structures can provide, and so that they also realise that expert advice and services from experienced designers and contractors such as are members of the MSAA, is essential for the satisfactory provision of even relatively small and simple projects.