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Summary

In the space of a decade, has been established in Australia a small industry concerned with the applications of flexible membranes, usually fabrics, in structures hitherto the domain of the 'noble' materials timber, steel, concrete and brick.

This paper briefly reviews both the development of engineered membrane structures and the characteristics which set them somewhat apart from other structures.

In particular, the technical requirements on design, materials and construction are referred to, together with comments on present and potential markets.

Membrane Structures - What are they?

What are they indeed, and why are they different from other structures? - are they different at all?

One of the best definitions (1) is that Membrane structures are those structures which employ a thin, flexible surface material, such as coated and uncoated fabrics, as their main structural and roofing element which is permanently stressed between its support system and its anchorages.

Membranes can be subdivided into two major groups:

(i) Non-prestressed membranes such as tents, sails and air-(or other medium) filled structures, which are originally slack in the unloaded condition and assume shapes of either single or double curvature when loaded;

(ii) Prestressed membranes such as tent and air supported or air-inflated structures which, in the case of prestressed tents, assume double negative (saddle) curvature, or in the case of air-supported or air-inflated structures under air pressure assume single or double positive (dome) curvature.

Being of flexible material, membranes must be either supported internally or suspended externally from rigid supports such as masts, frames, arches, walls, or from ground elevations; alternatively membranes may be supported by raising the internal air pressure underneath the membrane above atmospheric level.

According to the type of support, membranes may be further subdivided into point, line or surface supported.

The boundaries of membrane surfaces may either be bordered by edge cables or may be clamped directly to rigid structural elements such as edge seams, frames, compression rings, or on to walls.

Three important points can be made here:

(i) Just about all our conventional methods of construction employ a structural system of primary plus secondary frame elements plus an envelope. Note that in our definition the membrane is both structure and envelope, and this is one major difference which sets membrane structures apart from conventional structures.

(ii) The use of fabrics in other than small scale structures has, to a great extent been a transposition of the non-structural envelope principle noted above, i.e. a primary load-carrying frame has been erected and the fabric (membrane) merely fixed to it. In our definition of membrane structure the membrane does all the work, and it is this which differentiates true membrane structures from the vast range of fabric applications which form the basis of the 'canvas goods' industry. These are sometimes referred to as 'non-prestressed membranes'.

(iii) Note that a pre-stressed membrane is permanently 'stressed', i.e. it is not to be slack at any time. It is this element of permanent surface stress in an engineering sense which makes these structures different from all our conventional construction systems.

Yet, having said this and claimed that these structures are different, it is as well to remember that in the broadest sense any 'structure' is just a physical means of collecting and disposing of loads and of providing containment. Membrane structures should be thought of in these terms rather than in simple terms of stress, or one can very quickly be blinkered in assessing their worth and potential, or for that matter their shortcomings.

It is not uncommon, therefore, to see some structures referred to as membrane structures but which are not so at all. In our formative years we would be forgiven an occasional lapse born of enthusiasm, in labelling our non-prestressed cousins thus; but henceforth higher standards must be aspired to!

Of course, we must be careful that we know whether it is the 'fabric structures' industry or the 'membrane structures' industry that we are in. It could reasonably be said that in the present context we are all into fabrics, but only a few of us are into structural membranes.

The above differentiation between membrane and 'other' structures is not meant to imply that structural membranes will solve every practical construction problem. Not so, everything has its place. The total value of membrane structures in Australia is now and will remain into the foreseeable future a small proportion of that of the established 'flat fabric products' whose usefulness to and acceptability by the Public is undeniable.

With few exceptions flat surface elements cannot form part of a true membrane structure. This is an axiom of our entire design procedures.

Nevertheless, where scale of application increases, be it in terms of span, loading or environmental demand, the principals of membrane structures will be found to offer valuable, economical and visually pleasing solutions when thoughtfully applied.

It is becoming more evident as experience grows that membrane structures are offering not only improved solutions to many construction tasks but, on occasion maybe the only feasible solution.

General Development of Prestressed Membrane Structures

Because prestressed membrane structures are permanently tensioned they did not start to blossom until suitable materials and jointing methods were developed. Of course, this is a chicken and egg situation which means that suitable demands had to exist as well.

The Second World War spawned a lot of activity out of necessity, and at its end many opportunities presented themselves for application of new technologies to peaceful uses. Membrane structures was one of them.

From about 1945 onwards saw the first applications of fabrics as envelope and structure combined. The air domes of Walter Bird in U.S.A. at the end of the 1940's and the later four point sails of Frei Otto in Germany in the early 1950's were the prototypes from which the now worldwide membrane structures industry grew.

A large number of Bird's three-quarter spherical domes were built throughout the Northern U.S. and Canada. Bird went into business by establishing 'Birdair Structures, Inc.' and continued the development of the air structure through a number of commercial and military applications.

From its beginnings in the U.S., the air structure spread quickly to Europe where in 1959 its development was encouraged by Frei Otto and Peter Stromeyer, who had been co-operating since 1954 on a development of their own; the prestressed membrane tent.

As a result of the work Frei Otto published his book 'Hanging Roofs' in 1953. It became the first significant general work on lightweight tension surface structures, contributing to a subsequent revival of cable and membrane tension structures in architecture and engineering. It is interesting to note that the rising interest in tension structures from that time contrasted a falling interest in compression (shell) structures.

The close co-operation of the architect/originator Otto with the entrepreneur Stromeyer led to construction of totally new concepts in tents - the modern prestressed membrane structure during the 1950's and 1960's.

In the 1960's Otto published books on design and analysis of pneumatic structures and on cable-net structures, the principles of which were applied in the classic Montreal Expo roof in 1967, the U.S. air supported pavilion in Osaka in 1970, and the recent Haj Terminal in Jeddah in 1980.

Australian Development

The beginnings of contemporary membrane structures development in this country is generally agreed to have been in the late 1950's. Bert Bilsborough of Sydney, learned of Bird's air structures and, at a time when air structures were just being introduced in Europe, designed and constructed his first air-supported structure in 1958, with a newly developed PVC coated nylon fabric produced by ICI Chemicals.

Fabrics were, however, very much in use prior to this. The first membrane structures in Australia of any note were circus tents, first manufactured with the advent of circuses in Australia around the 1850's. The first circus tents were circular in plan with one central pole, but as the circuses grew in size, so did the tents, to 2, 3, 4 or more central pole supports. Since those early days of circus tents in Australia, their main features have not changed noticeably. In particular they are still made of essentially large flat panel fabric elements.

A variety of non-prestressed membrane structures where the membrane acts primarily as cladding on a frame have been erected in Australia. Amongst these were portable aircraft hangars and helicopter repair shelters, which were simple rigid frames of side walls and pitched roofs made out of steel members. Other non-prestressed, line supported membranes included exhibition spaces, ship covers for maintenance work, a dodgem car track cover, and quite recently an experimental membrane covered gridshell, the first such structure in Australia.

Prestressed membrane structures were introduced later about 1970. These included both point and line supported examples, such as display and shade marquees and covers, marquees at a shopping centre, racing car covers, an arts and crafts studio at a school, multi-purpose 'Tension Structures', reception canopies, walkway covers and outdoor stage roofs, a roof for a recreation centre, a courtyard cover for an hotel and an entrance canopy, an exhibition stand and a church roof, the first Teflon-coated fibreglass structure in Australia. More and larger structures of this type are being constructed.

Although air-supported structures were introduced to Australia in the late 50's their number has only recently started to increase. Earlier applications had been mainly for industrial use; some examples include storage structures, air-supported halls as travelling churches, maintenance and construction shelters, and several swimming pool covers.

In reviewing this it is important to note that the development of membrane structures has taken place in the very short space of just thirty years. Indeed it could be said that real activity in Australia has been limited to little more than half that time.

We must appreciate this lest we become too critical of what some may see as limitations in our technology and materials. For example, where some five years ago engineering design techniques based on model measurements and hand calculations left something to be desired, we now employ computer techniques with strong confidence in the answers obtained. Even so, continuous refinement in these methods is proceeding whereby more accurate, more economical and faster results will be obtained. For its size the Australian Industry has much to be proud of in its achievement to date in this field and for its enthusiasm to aspire to world standard technology when the occasion demands.

In materials too, whereas a decade ago saw fabric lives of 5 - 10 years as the norm, today we can offer 10 - 25 years, with total confidence that within this decade normal commercial fabrics with 15 - 40 year lives will be available.

Techniques of recoating to extend fabric lives have only just started to be looked at seriously.

Even though their economic analyses do not reflect it the vast majority of Clients still expect structures to last indefinitely. Our local Industry is then rising to the demands being placed upon it. By offering consistently good work we will soon gain a high degree of acceptability for membrane structures in this Country; at which stage we would have had some structures up for the apparently magical 10 years. We would then be firmly established.

We must be aware that we are still pioneers in this field even with the amount of Overseas evidence available both to Ourselves and to our potential Clients.

We have gone through a period of initial establishment and experimentation where most of our structures were relatively small and planned for short lives of say, 3 - 10 years. With structures of both larger scale and longer planned lives we have entered a proving period of considerable importance for all concerned.

Features of Contemporary Membrane Structures

The new generation of membrane structures is being expected to match in performance long established construction systems; there will always be a need for the small or temporary pavilions and interest 'features'; but from here on we must address the requirements of more sophisticated construction if our Industry is to attain maturity.

Experience gained from Overseas examples is helpful, and, in fact, to fail to learn from such experience is inexcusable. However, rarely can a solution from one part of the world merely be transplanted successfully in another. It is necessary to work through the full exercise to prove it from concept to construction.

The first change that is occurring is one of scale, e.g. 10m clear span of fabric is quite commonplace, 20m has been built, and larger are being planned. Larger structures with fewer supports mean heavy and bulky lifts, often with specialised equipment. This requires an extension of a Company's planning and operations abilities and, in particular, financing. Often such structures are not built in isolation and this requires close attention to contractural matters and liabilities.

Since we are talking mostly 'permanent' structures over valuable property we have not got the fall-back solution of rapidly lowering them if a severe storm is forecast. Consequently we are compelled if not by Local Authorities, then by our own ethical and commercial commonsense to design the structure rationally for quite severe and, in probability terms, quite unlikely loadings.

This in turn requires input of a brand of engineering not taught in the schools. It needs several years of 'apprenticeship' for an Engineer to be able to give useful service to a Contractor specialising in membrane structures. Conversely, it is not an easy task for a 'Converter' with long established and proven procedures to adapt to this new medium, not to mention the costs involved.

Of course, the more severe demands on our structures have meant more sophisticated membrane materials which require new handling and fabrication methods and equipment, and construction hardware to go with it.

Without doubt the higher the performance standards of a fabric the more critical is care in handling it from receival from the Manufacturer to final installation and maintenance. Such fabrics as PTFE/Glass and heavier top-coated PVC/Polyester cannot be given the rough treatment which canvas can withstand, e.g. sharp folds, but their ultimate performance is worth the time and effort. Again, these fabrics are usually incorporated into structures requiring a prestress level as much as ten times that of common marquee or similar long established applications.

Converters entering the membrane structures field will find themselves having to act at times as principal sub-contractor or even prime contractor and this introduces a new dimension to contracting, financing and erecting of membrane structures.

Finally, the finished cost per square metre of covered area for a fully engineered membrane structure is well above that of conventional tents; and on top of this the Client may demand a written guarantee to safeguard his investment.

Engineering of Membrane Structures

We have said that membrane structures require engineering, and the two principal areas of involvement are geometry and materials.

The basic rules governing the development of suitable form for a membrane structure have long since been established, i.e. briefly, open tension structures must have a permanent saddle or anti-clastic surface form, while closed or pneumatic structures must have either a domical i.e. synclastic form or be developable.

The one common feature of both of these is that flat surfaces are not theoretically permitted.

The word 'theoretical' has been introduced because today's technical society tends to recognise only numbers and calculations as the indispensable means of 'proof' of structural viability. One must, however, be aware of our limitations when it comes to describing a physical system with numbers. There are a great many things in the world which 'work' but which either have not or cannot be numerically quantified.

Nevertheless, as our structures venture from the temporary to the permanent, and each one is different from the last we are compelled to theorise the structure since there is no better accepted method. It must also be readily defensible on economic grounds even though building prototypes each time would be a great way to effectively double the Industry's workload!

Firstly, then, we have to derive a suitable surface shape for the structure. We need to combine the general criteria for structural membrane stability with the geometric limitations of the site and support system to arrive at an optimum form. We do this by so-called 'shapefinding techniques'.

Based on one's own knowledge and experience we must decide on either model or mathematical (usually computer) procedures to develop and define the correct surface.

The limitations of model techniques are selection of a suitable model 'membrane' and accuracy of construction and measurement. Nevertheless, physical modelling will long remain a valuable decision making and checking procedure.

With computer techniques the prime limitations are the mathematical model of the membrane materials, especially fabrics; and, on the local scene, suitable computer capacity to handle large and complex forms.

However, both techniques in spite of their limitations have helped the construction of every membrane structure to date, and so there is now quite a high degree of satisfaction with their continued effectiveness.

Most development is being directed to the computer area, and we may reasonably expect to see the 'instant membrane structure design package' available within five years, say, if present activity is sustained. (A word of caution, however is that it will not be cheap to obtain!).

Having derived a surface form we need to record it in a suitable fashion, and this is usually done as with any other construction activity by production of architectural and engineering drawings.

Such drawings may be of two classes:

(i) general pictorial and arrangement drawings; and

(ii) workshop and construction drawings.

At this time manual methods are being used to produce most drawings, however, computer drafting techniques are developing apace. Presently, general arrangement layouts, plans, views and sections can be produced in outline form by computer to be finished off by a draftsman. Cutting patterns and 'standard details' can be produced effectively by computer.

The rapid development of such procedures in Australia is stifled by the fact that we rarely build the same form of structure twice, and even if we did the funding to assist such development is severely limited.

Obtaining an optimised equilibrium shape and providing cutting patterns and hardware details is the main tangible result of the engineering input. However, to ensure the structure is sound it is necessary to 'analyse' it, that is, to derive the loads that will be imposed on the structure during its life, to carry out calculations to determine the forces in both the membrane and the support systems at all times, and to assess the movements or deflections which might occur in the structure under various loadings.

Only by carrying through such analyses can required fabric strengths, seams, edge restraints, cables, fittings, supports and anchorages be properly selected. It should be added that the results of such analyses need to be interpreted carefully from a background of experience.

We mentioned 'loads on the structure'. Physical loadings such as dead weight, wind, snow, earthquake, etc. immediately spring to mind. However, there are other physical factors which are equally important to the performance of a structure, viz. heat transfer (both in and out), lighting, acoustics, fire, UV radiation, amenity (wind environment, glare, colour, etc.) and other possible design considerations such as access and egress, demountability, cost, transport weight, erection feasibility etc. which all need to be resolved during the design and analysis phase. These are required of 'conventional' buildings and we must expect the same for membrane structures.

It can be stated that, at present not all these questions can be answered with the same cost-effective assuredness as for conventional longer established building forms where a far larger basis of experience and markets exist. Don't be fooled, however, there are a great many unanswered questions in all fields of building materials and construction systems, and ours is by no means poorly placed in this regard.

Because of the projected longer lives and higher permanent stresses in contemporary membrane structures the demands on the membrane materials are more severe than for, say, marquees and tents.

Both designer and fabricator have now to look carefully at all the membrane material properties and not merely the weight, tear strength and colour as hitherto may have been the case.

Degradation of membrane performance over time is a prime consideration at this stage; however, a great deal has been achieved, remembering the few short years that fabrics have been used in permanent structures, and one can reasonably look forward probably as little as 5 years to having powerful answers to the most commonly asked question by prospective Clients 'how long will it last'?

Accelerated weather and UV testing has shown that fabric materials can be selected to give a wide range of working lives, with the natural fibres at the lower end of the scale, through the now common PVC/Polyesters to PTFE/and Silicone/glass at the upper end. Valuable outdoor weather testing such as that reported in Ref. (2) is providing information not only on material breakdown with exposure but quantitative measures of strength retention which is critical to sound structural design.

Allied with this testing is an appreciation of the need for detailed design information on load/extension characteristics of fabrics, particularly their biaxial performance and the effects of seams and seam efficiency. One area in which the Industry would benefit from some investigation work is that relating to the application of 'reduction' or 'correction' factors to theoretically derived cutting patterns to arrive at the final workshop cutting patterns.

This need to define and measure many material and seam properties both new and aged, and their performance under fire, abrasion, etc. has created a demand for both testing facilities and useful basic standards to which we all may refer.

In striving to improve our design techniques we have recognised the need to establish an accurate measure of wind loadings on and flow patterns around our structures, which can only be obtained by careful wind tunnel studies. We are fortunate in having several well staffed facilities throughout Australia.

The whole question of 'standards' may be said to be in the melting pot. This applies to both technical and ethical standards.

Technically, a lot of standarised test methods have existed for some time in respect of fabric materials. These, however, were developed at a time when the extension of fabrics into the structures field as has occurred could not reasonably be envisaged and it is widely considered that they do not now adequately provide suitable measures for this application. In short, materials for structural membranes require knowledge of a range of properties not necessarily relevant to earlier fabric usages and these properties require the development and documentation of new test procedures.

Standards for the design of membrane structures are at present limited. Guidelines do exist Overseas for air-supported structures, however, there is no equivalent for tension membrane type structures. The relatively short history of membrane structures, and the wide range of geometric forms being built are largely the reasons for this lack of official engineering design standards.

A word of caution must be sounded, however, against establishing Standards for Standards sake. One has only to review activity in some areas of the construction industry to see that 'over-standardisation' leads to stagnation, and that is the last thing we want for our Industry.

The M.S.A.A. is very conscious of these points and is proceeding cautiously and thoughtfully on the matter of Standards, preferring to see a need for 'tentative guidelines' and an in-depth view of existing Standards at this time.

Onthe much broader matter of ethical standards it is being commented by many observers that the world community is sliding into another 'dark age', and as national economies get tighter evidence of this is not hard to find, particularly in the building industry. One would hope that our activities rise above that.

The Australian Market

Membrane structures including both open stressed and pneumatics have been employed by both public and private clients with the majority being for State Governments and Local Authorities. The Federal Government has so far been a minor supporter.

Activity has been strong in the three eastern States, but with two sizeable structures near completion in South Australia and Central Australia wider activity may be expected. Several projects have been proposed and planned to firm pricing stage in South Australia and Northern Territory but have not yet been proceeded with.

In New Zealand several small but notable structures have been completed and more are being proposed.

With the exception of the Yulara Project in Central Australia the majority of structures to date have been relatively small scale and one-off in nature. About 80% of the total value of all recent structures here have been tension rather than air supported membrane structures.

A small number of 'high pressure' air-inflated structures have been done.

The vast majority of structures have been for temporary application such as arcades, shade roofs, exhibitions, pool covers, band shells, etc.

Permanent membrane roofs have been installed for a church, school, motel, swimming centres and stage roofs.

At least two 'permanent' retractable membrane roofs over restaurants have been built and are proving highly successful.

Standard type air supported roofs have been built over swimming pools, sports hall and for storage purposes.

Plans are well advanced for some six medium sized permanent roof structures in location from Western Australia to North Queensland. It is important to note that for all of these projects membrane structures were specified from the start of planning rather than being offered as some form of cost-saving alternative subsequently.

An estimate of the value of recent membrane structures built in Australasia suggests that in 1982 it was \$0.7m, and in 1983 about \$1.3m. Present indications are that at least \$2.8m worth of fabric structures will be erected in 1984-85.

More than half of this market (in dollar value) is at present supplied from Overseas where a greater range of materials and fabrication facilities exists, in particular PTFE/glass fabrics. However, initial developments toward production facilities for such fabric structures have commenced here.

The constructed cost of membrane structures can vary between \$60/m² and \$360/m² of plan area. Since most are in the lower range it is evident that we are covering between 10,000 and 20,000m² at present.

The above figures suggest a healthy growth rate. While it is not easy to sell engineered membrane structures at this point in time we can expect this situation to change in the near future.

There are many projects in which a Client or Architect will independently decide on a membrane structure before approaching the Industry. However, there are a great many others where membrane structures would be sound alternatives if only the Designer was aware of their potential. We need, therefore, to keep up a strong program of education of Clients and potential Clients.

M.S.A.A. recognises that such promotion is as important to the Industry as technical achievement and promotes both aspects with equal vigour.

To accelerate the number of future membrane projects present markets must be developed and new applications must be found.

Well, it could fairly be argued that we have no identifiable exclusive market at present. Therefore, we must first and foremost nurture the Clients we have by doing good work for them and continuing to offer them information on new projects and material developments.

Support for the majority of projects to date has been provided by the Public Sector, and along with this support the standing and recognition of membrane structures as viable and economical alternative building systems.

It is hoped that this support will be continued and, indeed, extended at Federal level, so that the Australian Membrane Structures Industry, which at present lacks the funding and resources for accelerated technological change which is necessary to keep pace with market developments, can expand and develop to maturity and compete on an equal basis with Overseas Companies for Australian projects.

At present the building industry in Australia is in a negative growth condition, and whatever activity there is, is due to an artificially created high in the domestic field.

Maybe, therefore, the domestic area is worth investigation. Also, the temporary rental market could do with an injection of novel engineered designs. In Australia there is a great need for shade rather than for enclosure against elements as in many other Countries. With so many schools, resorts, shopping and sports centres being planned there are many opportunities for custom designed or standard range structures such as umbrellas, hypars and similar attractive yet simple forms.

At the other end of the scale, even though the number of large building and engineering structures is very limited at present, the opportunity should be taken to propose membrane solutions in these areas, however remote the probability of success. If our ideas do not find their way into this project then maybe they will plant the seed of a solution for the next!

CONCLUSION

It could be said that Membrane Structures in Australia have completed an initial trial period, and that a period of consolidation and assessment by both end users and all involved in their design and construction has commenced.

It is recognised that the value of the membrane structures market will remain relatively small for some time yet which must lead to a specialisation of activities. The once parochial Australian society has been largely broken down, and advances in transport and communications have made it quite practicable and economical for a small number of efficient specialists in design, fabrication and contracting to service the whole country.

While total construction activity worldwide is low at present it must be recognised that such times can offer opportunities for new ideas and techniques leading to improvements in quality and/or economy in our built environment.

A number of new key projects such as theme parks, high standard tourist and community centres, agricultural shade structures and national and international exhibitions are being planned, and these are expected to lead to an increase in demand for membrane structures.

As projects become larger and Clients more critical the need for truly contemporary technological input increases, and this need must be met by each section of our Industry if it is to fulfil its role as prime supplier to the Australian market.

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