"COMPUTER MODELLING - THE KEY TO SUCCESSFUL FABRIC STRUCTURES"

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INTRODUCTION

The theme of this conference is "Performance of Fabric Structures in Building Developments".

What one may ask is the significance of "Computer Modelling" to the achievement of successful long term performance of a fabric structure project?

Before we address that question it is worthwhile considering the aspects of fabric structure performance that either attract clients and developers to their use or on the other hand deter them in favour of more "proven", conventional structures. Having discussed the principal performance items the paper then describes how the latest computer software used by structural engineers with the necessary fabric structures experience can greatly improve the long term performance of fabric structures thus offering to the client a more predictable and durable product.

Advanced computer modelling is essential to correctly generate the fabric surface, to rigorously analyse the structure under the design loadings and to generate accurate cutting patterns for the fabrication of "wrinkle-free" surfaces.

Incorrect modelling of any of these aspects can seriously reduce the long term life of the structure and in this sense computer modelling is indeed the key to a successful fabric structure.

FABRIC STRUCTURE PERFORMANCE CHARACTERISTICS

Fabric structures whether they be pneumatics or tensioned fabrics can offer major advantages to building development clients compared with other more conventional structures. Their most attractive feature is their ability to provide an economic long-span translucent enclosure without the need for internal column supports. Furthermore where desirable an irregular "free-form" geometry can be utilised.

The only other viable free-form solution to such a problem is a cable net structure with translucent cladding such as glass or acrylic panels. Besides the risk of leakage through cladding joints which does not occur in the case of a fabric structure, the glazed cable net solution is significantly more expensive.

Even for intermediate spans of 10m - 40m fabric structures can compete favourably against a glazed steel frame or glazed spaceframe for example.

There are now a substantial number of fabric structures which have been constructed in Australia since their introduction in the 1970's performing a variety of functions including swimming pool enclosures, sound shells, shopping malls, travelling exhibitions, etc. Nevertheless, it is interesting to note that of the 1988 total building construction expenditure in Australia reported to be $20 billion, the value of all engineered fabric structures constructed in that period has been estimated as approximately $20 million. There is obviously enormous scope for expansion of the fabric structure industry and this requires a continuing improvement of the designs and their performance.

Connell Wagner through their involvement with projects such as the Bicentennial Travelling Exhibition, Expo 88 Vulture Street Canopy, Penguin Parade and Shell Westgate, have become aware of client perceptions about fabric structure performance.

It is important to remember that fabric structures must generally compete from both a cost and performance viewpoint with conventional structures.

A list of perceived fabric structure disadvantages and concerns raised by potential clients may include some of the following performance items:-

a) Perceived increased risk of structural failure due to high winds or other loadings.

b) Concern about the life of the fabric structure.

c) Environmental issues including internal condensation, air conditioning, heating costs and lighting.

d) Performance in fire and public safety.

Advanced computer modelling techniques can be used to significantly improve the structural performance of a fabric structures and address many of these concerns.

FABRIC STRUCTURE COMPUTER PROGRAMS

It is only during the last 15 years that the necessary computer software and hardware has been developed for the design and analysis of fabric structures. Prior to that time, only simple geometries (e.g., pneumatic cylinder) could be anlysed using basic "shell theory". Alternatively, scaled physical models had to be made to find the desired structural shape and compute the cutting patterns. Whilst physical models are still very useful to gain an understanding of a complex roof geometry and to quickly examine refinements the computer software in the hands of a skilled analyst is superseding their need and offering a much higher degree of accuracy.

Fabric structures are highly specialised engineering forms and as such require specially developed computer programs to analyse and pattern them. Generically they are a branch of the "Tension Structure" group which have little or zero capacity to resist either compressive or flexural forces and hence carry their loads soley by tension forces. Other examples of tension structures include cable stayed and suspension bridges and cable net roofs.

To achieve force equilibrium tension structures undergo relatively large deflections compared with more "rigid" conventional structures. Whereas the latter more or less maintain their initial geometry under load, fabric structures by their very nature must change shape to carry the external loads such that the membrane remains in tension.

This change of shape characteristic means that fabrics cannot be analysed by conventional "linear elastic" programs which base the analysis on the original geometry. Instead they require the more advanced "large displacement theory" programs which model the surface geometry changes and by an iterative process progress to the final equilibrium position.

In addition, fabric structure packages should permit the automatic generation of "free-form" surfaces and most importantly must be able to produce the necessarily accurate cutting patterns from which the fabric is manufactured.

There are now a number of fabric structure computer packages being operated by design/fabricator groups in Australia and there is no doubt that the necessary analytical expertise is available locally. No longer is there a need to go overseas for the technology.

As an example, the following describes the "TENSYL" package being operated by Connell Wagner through its associated company Connell Barrow McCready. "TENSYL" is leased from the U.K. based consultant Minitec Pty. Ltd.

With reference to figure 1 the program models the fabric surface as a mesh of triangular finite elements whose edges are defined by a series of geodesic lines.

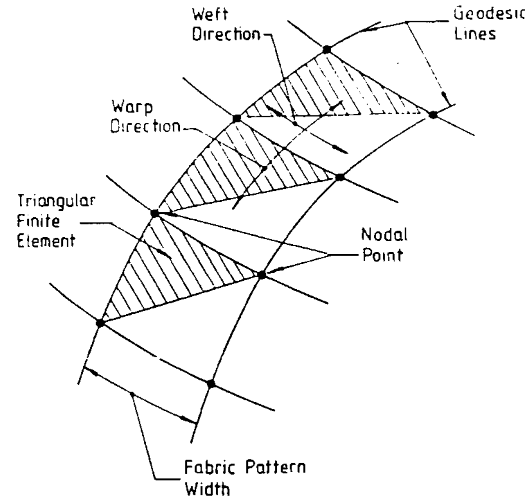


FIG.1 –"TENSYL" FINITE ELEMENT MESH

Cables are modelled as line elements which can either be "connected" to the fabric or modelled as a "slip" ridge cable which strains independently to the fabric. "TENSYL" can also accommodate a variety of support elements in the overall computer model including suspended ring beams and guyed back masts for example as shown in Figure 2. This is a powerful facility because the overall problem can be modelled as opposed to analysing the fabric and support structures separately and then manually combining the analyses and trying to achieve the compatibility.

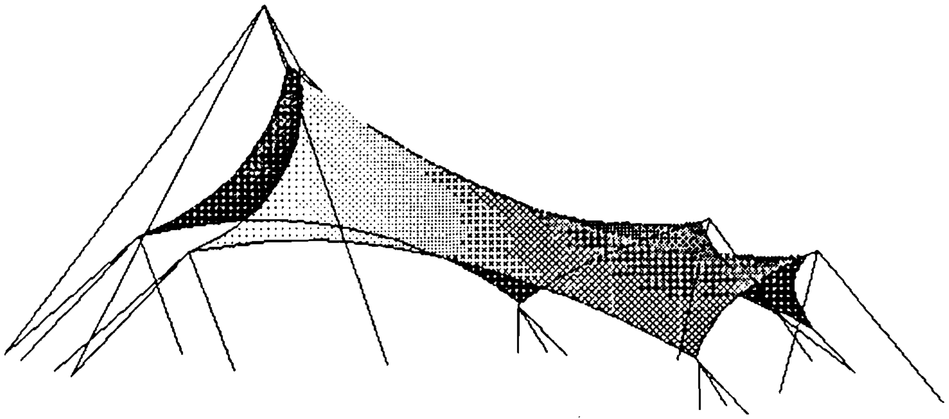


FIGURE 2
VULTURE STREET CANOPY, EXPO ́88 – PERSPECTIVE

As with all analysis the mathematical model is an approximation to the actual physical reality and it is important to keep this in mind when designing and detailing the structure.

"TENSYL" differs from other computer packages because it uses the Dynamic Relaxation vector method of analysis as opposed to other programs which use a matrix method of analysis. Whilst the latter technique can require input of a relatively accurate initial fabric geometry the Dynamic Relaxation method only requires the user to specify the mesh layout, support point geometry and the fabric prestress. The program then automatically generates the curved free-form surface through a series of iterative steps. An example is a pneumatic structure, for which a flat mesh can be input and then the program literally "inflates" the fabric into its equilibrium position.

A further advantage of the Dynamic Relaxation technique is that it only needs to store the current values of nodal force and displacement and consequently the problem can be interrupted, modified and restarted at any point of the formfinding or analysis.

"TENSYL" is an iterative interaction program sub-divided into three stages which are integrally linked and allow the user to move sequentially through a problem.

Stage 1 - Formfind the fabric along with its associated support steelwork either as a:-

a) Tensioned Fabric doubly curved surface between specified support points with designated fabric and cable prestress forces. The program allows the fabric prestress to be varied throughout the membrane to permit locally increased curvatures at support points for example.

or

b) Pneumatic (air supported) structure by specifying both the prestress forces and the internal air pressure.

At this stage 3-D computer graphics are produced enabling a visualisation of the surface and refinement as necessary.

Stage 2

Load analyses are performed on the form found structure. Strength and deflection serviceability checks are carried out at this stage.

Stage 3

Cutting patterns are produced by unfolding the 3-D finite element mesh on to 2-D rolls of fabric. Accuracy is paramount, typically in the range $\pm$ 1mm.

It should be noted that as the computer software improves there will be less and less dependence on physical models during the design stage.

THE IMPORTANCE OF COMPUTER MODELLING TO ENSURE SUCCESSFUL STRUCTURAL PERFORMANCE OF FABRIC STRUCTURES

As with all structural modelling and analysis, there are two basic components namely:-

(i) the computer software
(ii) the skill and experience of the analyst in the field of fabric structures.

Both these components are crucial to a successfully performing fabric structure.

Without access to sophisticated computer software the problem cannot even be tackled except for the very simplest of geometries subject to uniform, usually unrealistic loading patterns.

From an engineering viewpoint these structures are highly demanding. For "conventional" structures the geometry (form) is generally pre-determined whereas in the case of fabric structures the structure is the form and vica-versa. The structural engineer must therefore be involved from the outset in the determination of a high quality fabric geometry.

Hence, the analysts' skill is equally important requiring close knowledge of fabric materials, fabrication and detailing and being able to realistically transform these physical characteristics into a mathematical model.

From a structural point of view, long term performance is dependent on a number of factors.

(i) First and foremost it is essential to ensure that the various structural elements, that is the fabric, cable and support steelwork have an adequate factor of safety against failure under extreme low condition. This obviously requires accurate computation of the structure stresses by the modelling techniques previously described. Allowance must be made for the fabric's strength reduction with time.

For the fabric design it is essential to know these stresses throughout the surface particularly at stress concentrations, such as, connection points. "TENSYL" allows the introduction of additional finite elements part way through the analysis to better define the model as necessary. As an example, Figure 3 shows the fabric element pattern for one of the Shell Westgate structures.

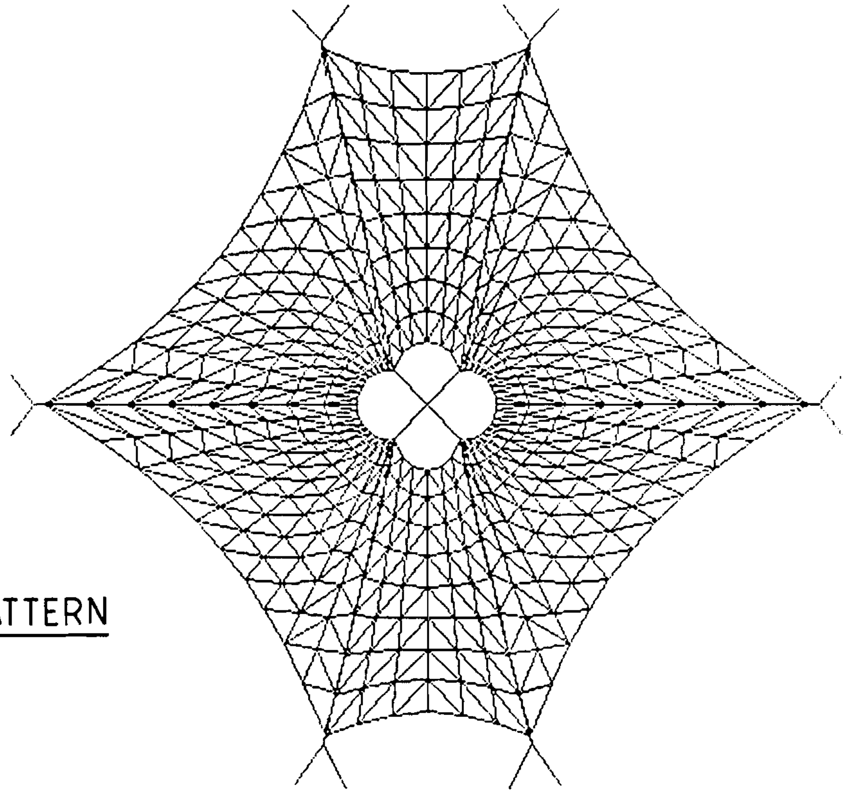


FIGURE 3

TYPICAL FABRIC PATTERN

(ii) Fabric curvature:- It is important to generate a wrinkle-free, well curved surface with smooth transitions. This is because the fabric stress is inversely propositional to the roof radius of curvature. An increased curvature therefore reduces the stresses for a given load increasing the factor of safety against tensile failure and improves the long term structural performance of the membrane. Equally important an increased curvature significantly stiffens the structure, thus reducing the tendency to "flap" in the wind and resulting in a more serviceable structure.

Advanced computer modelling allows the designer to vary the curvature throughout the roof surface during the formfinding process if excessive deflections or fabric "slack areas" are detected under load.

(iii) The designer must ensure adequate roof slope to discharge rainwater in the desired manner and to avoid "flat areas" which could result in water ponding during a downpour.

(iv) Overseas investigations have indicated that the majority of fabric failures initiate as a tear often at a connection and then propagate throughout the roof surface. Hence the importance of the tear strength in addition to the fabric tensile strength. It is therefore important that the connection detail provide a relatively smooth force path from the fabric to the support steelwork and avoid stress concentrations.

Figure 4 shows a typical membrane plate details which Connell Wagner and Connell Barrow McCready have used on a number of projects. The plate collects the reactions from the fabric, edge cables and their associated webbing and ridge cables where applicable. In addition, it provides 3 directional movement facility and tolerance to the various elements allowing them to move freely without any additional stresses.

Referring to the Figure 4 detail it is obviously essential that the various plate angles are computed to a high degree of accuracy from analysis and fabrication points of view. For example, a cable angle error of only a few degrees could cause secondary bending stresses in the cable and reduce the safety factor against failure.

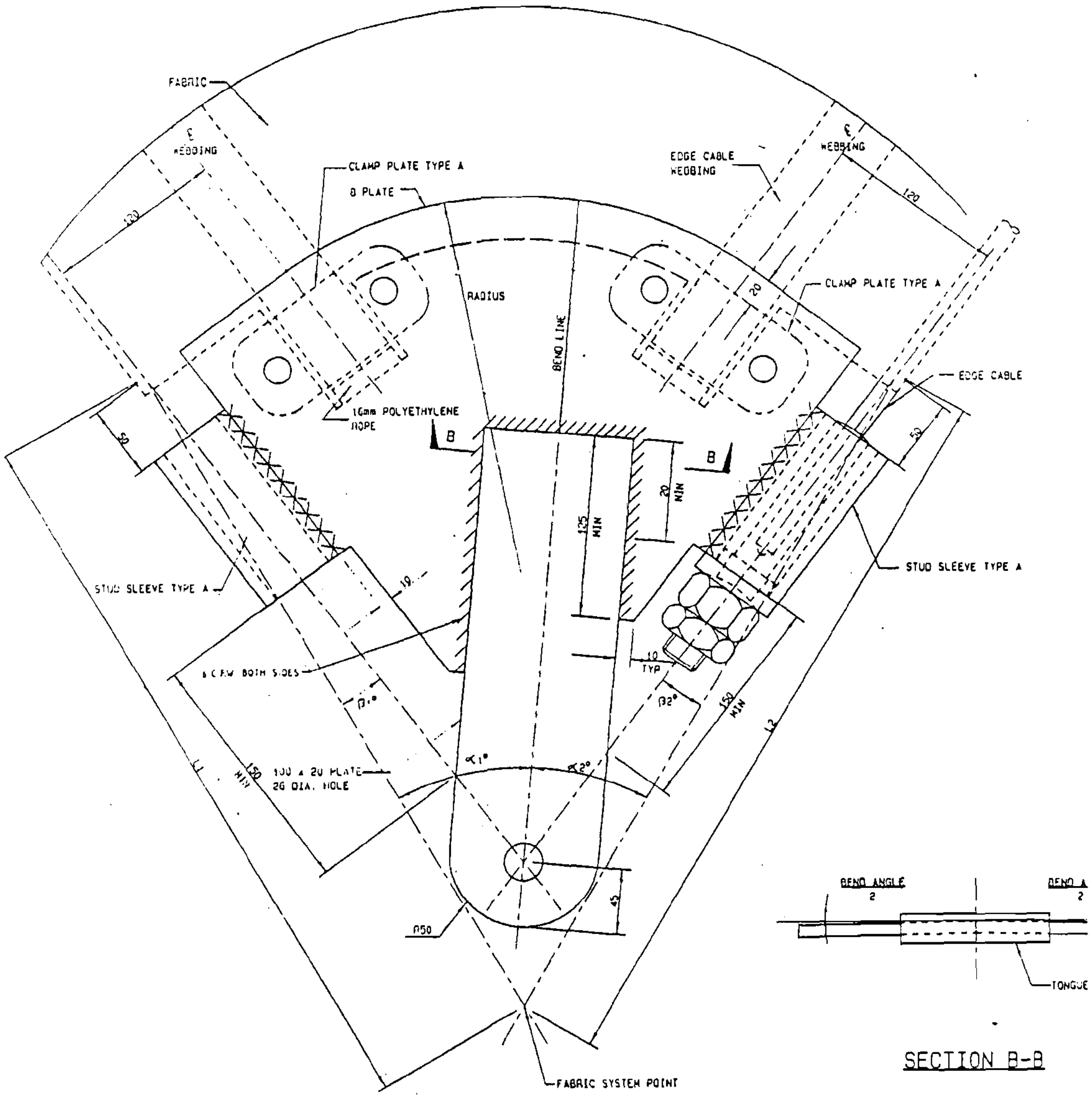
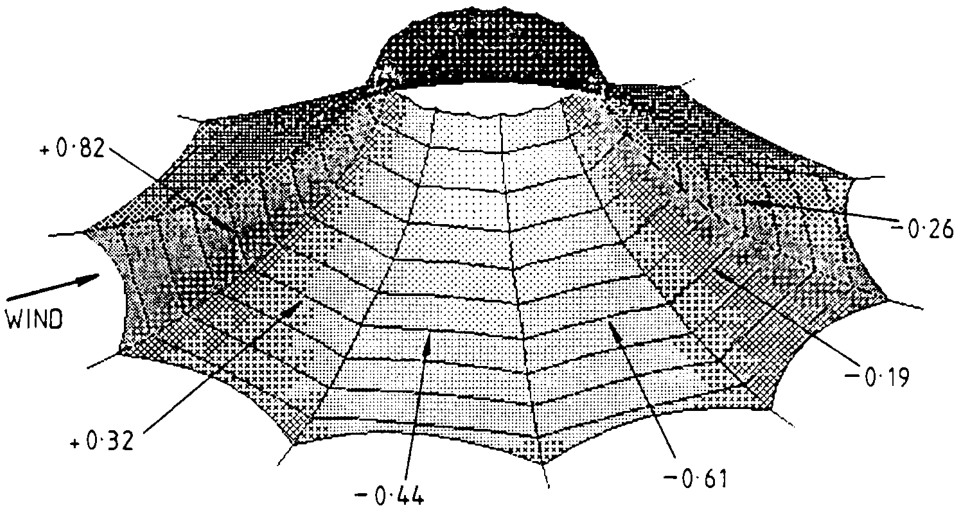


FIGURE-4. MEMBRANE PLATE

(iv) Analysis of complex loadcases:- In Australia, apart from Alpine areas, wind is the governing load case for lightweight structures. As an example, Figure 5 shows the wind tunnel pressure diagram for the Bicentennial Travelling Exhibition Theatre Structure. As is typical of a doubly curved geometry the pressures vary significantly across the membrane surface and often wind tunnel testing is required.

Such complex loadcases can only be analysed by the advanced modelling techniques previously described.

FIGURE 5 – WIND PRESSURE DISTRIBUTION FOR BICENTENNIAL THEATRE LOWER CONE



(vi) Satisfactory structure preformance requires a serviceability check to ensure that the fabric movements under the 1 year return period wind for example are kept within acceptable limits. To compute such deflections with any degree of accuracy, "large displacement theory" analyses are required. It is important to ensure in the limit state wind adequate minimum clearances between the fabric and adjoining rigid structures to avoid the development of fabric tear and possible overall failure.

(vii) The final stage of the modelling is probably the most important namely the production of the fabric patterns for fabrication.

With reference to Figure 1, the fabric patterns in "TENSYL" are bounded by two geodesic lines running in the warp direction. Part of the modelling skill is the selection of the optimum finite element mesh and pattern widths which will provide the necessary curvature, but at the same time for economy minimise fabric wastage.

Fabrics are anisotropic in that the weft elongation is several times higher than the warp elongation due to crimping effects. The warp/weft directions should therefore be aligned along the principal force directions to ensure that the fabric stretch is as uniform as possible and to ensure compatibility between adjacent fabric rolls.

The test of the computer modelling skill is the quality of the patterned structure and the formation of an evenly stressed wrinkle-free surface.

CONCLUSION

It is probably true to say that fabric structures have only recently come of age firstly because of rapidly improving fabric technology and secondly due to the latest generation of computer programs.

There is no doubt that fabric structures still have a long way to go to gain general public acceptance, but the key to successful fabric structures will continue to be advanced computer modelling techniques.