Tension Membrane Structures
Design Basics, Traps and Pitfalls

Joseph Dean
Director - Wade Consulting Group Pty Ltd
Brisbane, Australia

(The following represents the notes for the dialogue of a slide presentation and is included to provide a reminder of the content of the presentation – if further information is required please feel free to contact Joseph Dean at Wade Consulting Group, email joseph@wadeconsult.com)

INTRODUCTION
The intention of this talk is to provide an insight into the design of tensioned membrane structures and to highlight some of the traps and pitfalls.

The Wade Consulting Group has been involved in tension membrane structure design for about 14 years. Our work in this area commenced with the design of the Primary Industries Pavilion and some other minor structures for EXPO 88 in Brisbane.

Since our early beginnings, we have worked with numerous fabricators to produce hundreds of fabric structures in various styles, shapes and sizes. Thanks are due to those companies for those companies for allowing us to work in this area.

We work for numerous Australian contractors often as technical sub-consultants in design and construct packages and directly for architects. We also provide various levels of engineering, design and patterning services direct to membrane fabricators in many countries around the world.
Tension Membrane Basics

FABRICS
The primary element that is unique to this type of structure is the fabric. Architectural Grade fabrics are available in a range of weights, strengths and are made from a variety of materials.

- Knitted Shade Cloth
- PVC/Polyester
- PTFE/Glass
- ETFE Foil
- Wire Mesh

The two primary fabrics used in this industry are PVC coated polyester and Teflon coated fiberglass. PVC/Polyester fabrics are generally cheaper than the PTFE/Glass alternative but do not last as long. Depending on exposure and service conditions, one could expect about 10 – 15 years from PVC/Polyester and 30 years plus from PTFE/Glass.

BASIC DESIGN PRINCIPLES
There are two important principles to keep in mind when working with tensioned membrane structures, tension and shape.

TENSION
Fabric must have pre-tension in order to provide a ready medium to resist applied loads such as wind, rain, snow, etc. If there is little or no tension, a structure may have numerous wrinkles and will not perform well under applied loads. Apart from the aesthetic deficiencies, the lifespan of a structure can be compromised if there are numerous wrinkles or lack of tension.
Fabrics are generally stressed biaxially or tensioned in two orthogonal directions. High stress in one direction and inadequate stress in the other direction can result in wrinkles.
The target stress state in design is equal stress in both directions.

SHAPE
The importance of adequate shape or curvature in the surface of a membrane cannot be understated. Anticlastic curvature is defined as equal curvature of opposite sign in two orthogonal directions. Anticlastic curvature provides shapes that are most efficient in resisting applied loads. Very often, a structure will not have true anticlastic curvature but a version of it with some degree of opposing curvature in different directions. Anticlastic curvature also provides for even stresses in each direction.

Double curvature provides a ready load path for resisting applied loads and gives optimum deflection control. The higher the pretension in a doubly curved surface the lower the deflections for a given load.

A common mistake by newcomers is to use flat panels of fabric. Flat panels need to move significantly under wind loads in order to take up sufficient curvature to resist the applied loads. These large movements besides being visually alarming on a large structure can cause high stresses at the connections. In gusty and high wind conditions cyclic movements can quickly fatigue connections and lead to failure of the membrane.

Flat panels may be susceptible to ponding rainwater, snow or hail if there is insufficient slope. Ponding can occur during relatively light rainfall because of the relatively large displacements under minor loads. A minimum slope of ten degrees should be adopted.

A consequence of having high curvature in a structure is that the patterning becomes more difficult i.e. the process of forming the shape from flat strips becomes more involved. In such cases, generally narrower patterns must be used. Narrower patterns can mean more labour and more material wastage.

As engineers we often over indulge in straight lines, curves are de rigueur in tensioned membrane structures.

BASIC SHAPES
A number of basic shapes are widely used in tensioned fabric structures. These shapes are employed either alone or in combination to satisfy the project criteria and achieve sufficient surface curvature.
(Various examples of each of these shapes are illustrated in the slide presentation)

HYPAR

The first of these is the hyperbolic paraboloid or hypar. Hypars are characterized by having four or more points at different levels and not in the same plane. As a rule of thumb, we try to have minimum shape of approx 1 to 5 in height difference to length.

CONE

Another basic shape that provides double curvature is the cone. Cones provide different degrees of curvature in different directions. For this reason they often have varying prestress approaching the apex. Cones with under fabric cables have more even prestress but a more faceted shape.

BARREL VAULT

A barrel vault is characterized by fabric stretched over a series of arches. When a uniform biaxial prestress is used, the radius of the sagging fabric between parallel arches will be equal to the radius of the arch.

HYBRID

Some structures employ a number of the basic shapes in combination in the same structure. In this way, complex interface problems can be solved and focus can be given to a particular part of the structure if required.

OTHER SPECIALIZED FEATURES AND DETAILS

Besides the basic shapes taken up by the membrane, there are a number of other details and features used in tensioned membrane structures. Some of these are borrowed from sailing and rigging applications while others are uniquely developed for tensioned fabric. Some of these include: -

- Edge & Guy Cables
- Corner Clamping Plates
- Bale Rings
- Patch Fittings
- Bow & Dee Shackles
- Rigging Screws & Custom Fittings
- Clamping Bars
- Aluminium Extrusions
- Screw in Anchors

All successful details will account for any the required movement during tensioning and in service. Often one off solutions need to be developed to accommodate a multitude of incoming cable, steel and fabric elements. This design process requires careful thought and a proper accounting of all incoming forces.

DESIGN

Computer aided design has facilitated quick progress and increasing production in this industry in the last 20 years. Early structures were analyzed by approximate and hand methods combined with physical modeling. Modern design utilizes large displacement finite element modeling with software specifically written for membranes and cable nets.

By quickly generating a finite element model of a structure a designer is able to quickly assess the viability of a scheme and determine if the shape, runoff and load carrying requirements are satisfied. It is common for a client's starting geometry to undergo some adjustment to obtain enough shape for stability and adequate drainage.

Applied loads based on the loading codes, some wind tunnel data, and various research areas are applied incrementally to large displacement finite element models to determine internal loads and reactions. The magnitude of displacements is often much greater than experienced in conventional structures but that is the nature of lightweight structures. No code requirements exist for deflection limits so it often comes down to the judgement of the designer.

PATTERNING

Early patterning was done by carefully working from scale models. The patterning process has benefited substantially from computer based finite element form finding and computer plotting and cutting of full size patterns. Any patterning process is trying to approximate the finished surface with flat strips.

TRAPS AND PITFALLS

The following is a quick list of things to be aware of when considering the design of a tensioned membrane structure: -

Point loads will probably be bigger than you first think.	Reactions from fabric structures can be quite large – even the prestress forces. We've seen a number of failed jobs where the reaction loads have been underestimated with tragic consequences in terms of property damage. Undertake a proper analysis of the structure using the large displacement finite element method.
Water Runoff / Ponding	Without adequate slope a fabric structure can easily pond. The ponds can just keep growing until something breaks. Change the geometry or increase the prestress until it doesn't pond.
Hail & Snow	Same as for ponding
Shape / Flapping	Flat fabric will flap or flutter under high wind conditions, this invariably leads to failure. A fabric wholesaler once commented that one of the sweetest sounds he can imagine is the flapping of an unsecured tarp on a trailer.
Rotational Freedom / Fatigue	All fixings need to allow adequate freedom for rotation in service and during erection.
Integrity of Supports	Supports need to account for sustained prestress loads as well as transient design conditions. A small rotation in a footing can mean the difference between a properly tensioned functional structure and "a bed sheet temporarily on the clothes line".
Careful connection detailing	A prime source of failure in tensioned membrane structures is poor detailing. Sharp edges that can damage fabric, eccentricities, and inadequately sized fittings are all areas that can create problems if not well thought out and designed properly.
Geometry Control	Spend a bit more time/effort on the survey or measure up and get it right the first time. Fabric can be unforgiving when geometry control is poor, precise geometry control is critical to a successful structure.