From Theory Through to Practice: Tensioned Membrane Structures in Singapore

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INTRODUCTION

Skyspan (Pacific) have been fortunate over the last couple of years to do over a dozen projects in Singapore. These have ranged from vertical hypar sails, barrel vault shaped canopies, and stand alone conics to long walkway structures. This range of structures gives us an ideal opportunity to be able to illustrate the theory behind the design of tensioned membrane structures, and to outline the basics of design and detailing to required achieve successful structures in practice.

SHAPE AND FORM

To provide stable forms, the fabric skin in tensioned membrane structures must be stressed into anticlastic (doubly curved) surfaces, where there is opposing curvature in orthogonal directions. The basic form is known mathematically as a hyperbolic paraboloid, or hypar.

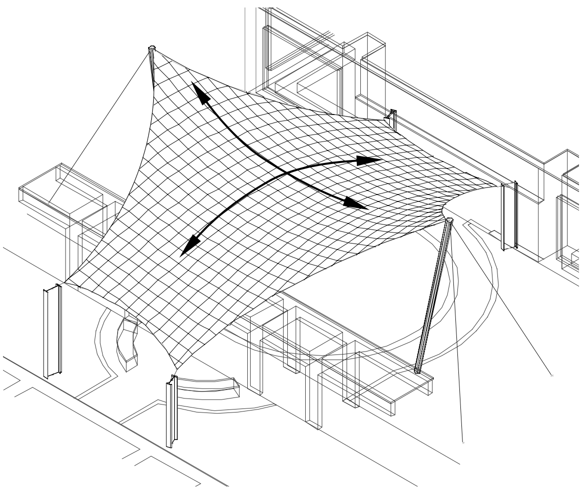


Fig 1: 6 point Hypar – IUP Bedok Rd

Fig 2: Pair of Hypars to Central Mast
Sail C - Waterfront Condominiums

These forms are minimal surfaces between the defined boundary support points. The opposing curvature allows the structure to carry externally imposed loads, such as wind and snow. For example, considering the 6 point hypar in figure 1 above, downward snow loads are resisted by an increase in the fabric stress in the direction between the high points and a decrease in the fabric stress between the low points, whilst wind uplift loads are taken to the low points.

The flatter the fabric surface (i.e. the smaller the difference in height between the high and low support points, the greater the fabric stresses and resultant loads will be at the corners. The deflection of the structure will also be greater.

The other main groups of anticlastic shapes are conics and barrel vaults (including cross arches), examples of which are illustrated below:

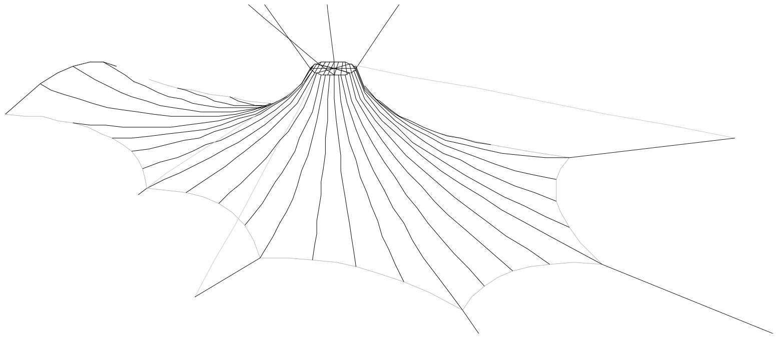


Fig 3: Conic with arch at one edge – IBP2 Entry Canopy, Jurong East

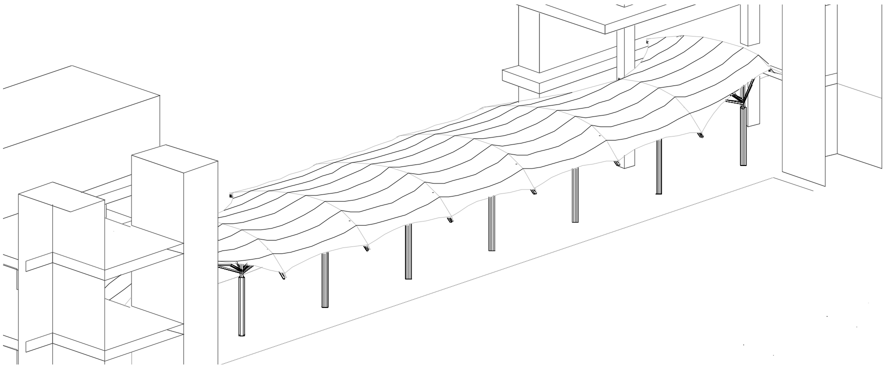


Fig 4: Barrel Vault – Ngee Ann Polytechnic Linkway

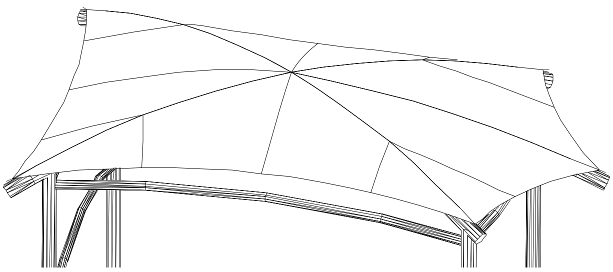


Fig 5: Cross Arch – East Meadows Condominium Walkways

Inflatable structures are a second distinct category of tensile membrane structures, in which the interiors are pressurised to form doubly curved surfaces with similar curvature in orthogonal directions (i.e. synclastic forms).

MATERIALS

Fabric

The fabric for tensioned membrane structures can be broadly divided into three main groups - coated fabrics, films and meshes.

A coated structural fabric usually consists of a woven base cloth stabilised and protected by a coating. The base cloth usually consists of warp threads running the length of the roll with fill (or weft) threads weaved across.   For external use the choice is commonly between using PVC coated Polyester cloth or PTFE (aka Teflon) coated glass fibre fabrics.

These two principle fabrics of the tensioned membrane industry are deserving of entire papers on their properties and performance alone, but here is just a brief listing and comparison of some of their main features.

Feature	PVC coated Polyester	PTFE coated Glass Fibre
Life Expectancy	Quoted lifespan is based on visual appearance, usually 10-15 years	25-30 years.
Fire	Will not support combustion, nor produce flaming droplets. Fire rated to AS1530.	Non-flammable. Fire rated to Australian Standards AS1530 – Class 0-1.
Light Transmission	8 to 16% depending on fabric grade. Blackout fabrics sometimes available.	8 to 15% depending on fabric grade.
UV Resistance	UV stabilisers limit deterioration	Unaffected by UV radiation once initial bleaching occurs.
Manufacture	Easy to fold and handle. Seams made with high frequency welders	Care required to avoid permanent creases. Seams made with hot plate welders.
Erection / Transportability	Can be tensioned in one operation, and with its flexibility it is ideal for temporary structures.	Requires slower staged tensioning. Glass fibres makes it unsuitable for temporary structures.
Cleanability	PVDF lacquers enhance cleanability, but plasticisers will migrate towards surface over time making harder to clean.	Inert and low adhesion surface, making it relatively self-cleaning in rain.
Colour	Wide range available on light grades, and with surface areas >2000-3000m^2 for heavier grades.	Standard white. Note: beige when new, bleaching to white in few months exposure to direct sunlight.
Cost and Supply	Readily available from a number of suppliers for A$10-20/m^2, depending of quantity, grade etc.	Fewer suppliers, and cost A$80-120/m^2, depending on quantity, grade, etc.

Films are transparent polymers supplied in sheet form and are not laminated or coated (eg. clear vinyl, ETFE, Polyethylene). They are cheaper than woven coated fabrics but not as strong or durable.

Meshes are porous fabrics, usually either a coated fabric with spacing between the thread bundles, or as woven/knitted fabric using high-density polyethylene, polypropylene or acrylic yarn. Being porous they do not provide rain shelter, but the woven fabrics are cheaper, require less engineering and patterning and have thus become very popular as temporary sunshade structures.

Cables

Cables are typically used in a number of locations in tensioned membrane structures including along free edges, internal ridge and valley lines, as supports of flying masts and as tiebacks of perimeter steel masts to foundations or supporting superstructure.

Cables are typically galvanised or stainless steel, although Galfan and Kevlar cables are also available. Cables are available in a range of construction, each having different stiffness, strength, and flexibility, and suited to different tasks.

Strand – This is the stiffest and strongest type of cable, and is best suited for edge catenary cables and guying purposes where stiffness is key. Connections are limited to swaged and drop forged sockets type due to the stiffness of strand.

Wire Core Wire Rope – More flexible than strand, stiffer than fibre core, this is the wire rope in the middle. The full range of connections is available for end terminations.

Fibre Core Wire Rope – The most flexible type, but swaged end connections cannot be used.

Stainless Steel Wire Rope – Stainless steel wire rope is produced in grades 304 and 316 in 1x19, 7x7 and 7x19 construction. Grade 316 is marginally more expensive, has superior corrosion resistance and appearance, but slightly lower load capacity. Cables are readily available in sizes from 3 to 26mm diameter.

Fig 6: Cables and Fittings – IBP2 Entry Canopy, Jurong East

Fittings

Fittings are used to connect the fabric to the supporting structure.

For free form structures with discrete supports the fittings provide a flexible and adjustable connection, principally using shackles, chain links, rigging screws, turnbuckles, threaded toggles, or U-bolts. The fittings are typically galvanised or stainless steel, usually in line with the material selected for the cables.

For fixed edge structures the fabric can be fixed by continuous clamp plates or with a purpose made section. This can be from steel or aluminium. A number of fabric fabricators offer specialised extrusions.

Steelwork, Concrete & Foundations

Steelwork, concrete and foundations supporting tensioned membrane structures are designed using the relevant codes and standards for the structure.

For medium and large structure steel is the most efficient way to carry the significant loads generated from the fabric. It can be detailed to handle the tensioning and tolerance requirements and typically is more architecturally sympathetic with the structure.

BASICS OF DESIGN

Formfinding

Tensioned membrane structures can often appear deceivingly simple, yet are complex structures requiring an ability to think and work in 3D. In days past stocking models was the stock-in-trade of the tensile membrane structure designer. It can still be a very valuable tool, although the use of computer programs for the formfinding and analysis has become the norm.

Some of the key design criteria to consider when formfinding a tensioned membrane structure are:

1. Is there adequate curvature to limit maximum fabric stresses and movements to acceptable levels.
2. Is there adequate slope at perimeter, and curvature throughout structure, to prevent ponding of water on surface of the structure?
3. Is there sufficient angle between the edge cables into each corner collection plate?
4. Do the edge cables have appropriate drapes (usually between span/8 to span/15)
5. Is the fabric clearance to supporting steelwork and surrounding fixed structures adequate?
6. Have the height clearance requirements been met.
7. Has the method of erection and tensioning of the structure been considered with regard to how it impacts the form and support system of the structure?
8. Do the aesthetics of the structure meets the client's brief and architects desire.

Pretension

Pretension is defined as the tensile forces in the fabric after erection but prior to external loads being applied.

The ratio of prestress in the two principle directions, which dictates the local shape, is usually established in the computer form generation process. The absolute values of prestress required is calculated to be sufficient to keep all parts of the membrane in tension under any design serviceability loadcase.

As noted in the previous section, the imposed loads are resisted by a redistribution of the stresses within the fabric. Care must be taken to ensure that stresses in one direction do not reduce to zero, as this implies uniaxial stresses, and therefore wrinkles. It is also an indication that substantial and possibly excessive movement of the structure is occurring.

Analysis

Over most of Australia the critical design loading is wind. The current Australian Standard on wind actions is AS1170.2 - 2002, published in July. It is very detailed and can be used to determine relevant design wind pressures and coefficients. It even has pressure coefficients for a standard hypar canopy.

Designing for a snow or sand load requires more care, as there is a greater risk of the melted water ponding or getting sand build-up (which can cause permanent stretching of the fabric skin). In these circumstances the fabric forms generally need to be steeper, spans smaller, curvature greater and sometimes internal ridge and valley cables introduced.

For large multiple panel structures, consideration needs to be given to the effects of the loss or removal for repair, of any one of panels. Also, other loadcases such as temperature differential, partial stressing, and erection sequence may need to be considered, as deemed appropriate.

Design

Fabric – Structural fabrics typically have a tensile strength ranging from 60/60 kN/m (warp/fill) up to 200/160 kN/m.

A factor of safety of 4 to 6 is usual on the maximum fabric stresses from the analysis of the design loadcases to select the grade of fabric required. A lower factor of safety can be used where the fabric stresses are from very transient (short term) loads such as wind, whilst higher factors of safety are recommended for longer-term loadings, such as snow. Many computer analysis programs give stress plots, similar to that shown below, to enable the stress distribution to be examined, and any stress concentrations to be observed and reinforcement detailed.

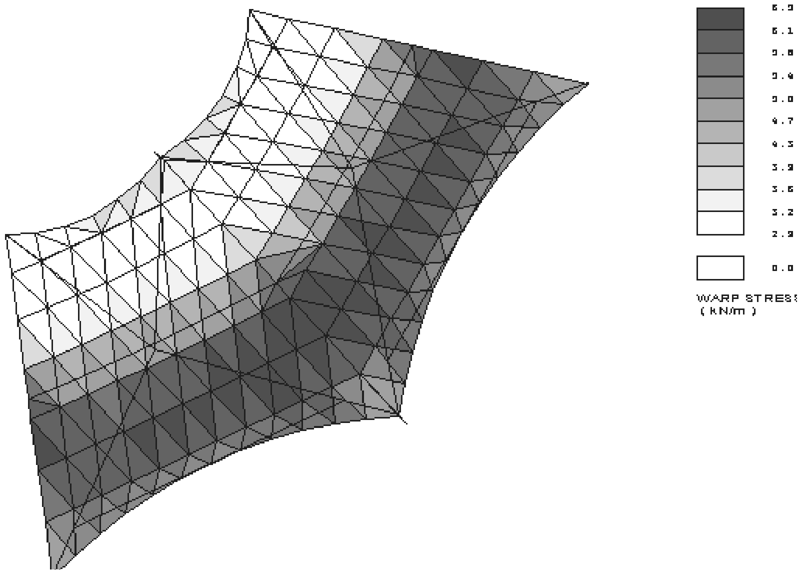


Fig 7: Typical Analysis Stress Plot – Forest Hill Condominium Entry Canopy

Cables – Cables being always under tension in tensioned membrane structures, are not exposed to shock loadings. This enables much lower safety factors to be used than required for lifting and general rigging applications. There appears to have been an acceptance across the tensioned membrane industry of a standard factor of safety of about 2.0.

Fittings – Being discrete items with a greater tendency of brittle failure, it is usual for fittings to have a larger factor of safety applied to their design than cables, typical in the range of 2.2 to 2.5.

Steelwork and Foundations – These elements should be designed in accordance with the relevant standard or code.

BASICS OF DETAILING

Canopies tend to fall into two main types, those that transfer tensile loads into adjacent structures and those containing the tensile loads within their own frame.

The first type can generate large lateral loads that may result in the need for additional checking and reinforcement of adjacent structures. Likewise this type of canopy with perimeter masts stayed with tieback cables to ground will generally need large mass concrete foundations or some system of The latter tends to balance the tensile forces within the system, reducing the need for tiebacks and other external retaining elements.

Selection of the materials used will depend on the:

- required life span of the structure/building,
- surrounding environment (i.e. sun, humidity, pollution levels)
- required fire performance
- possibility of vandalism
- level and frequency of scheduled maintenance

Other items to be considered are the tolerance requirements and the access and proposed method of erection of the structure.

Edge Details

Scalloped/Catenary Edges – These generally consist of a cable sitting in a pocket at the edge of the membrane. In some structures (especially in PTFE/Glass) an alternative is to have the edge cable exposed and connected to the edge of the membrane by a series of stainless steel link plates.

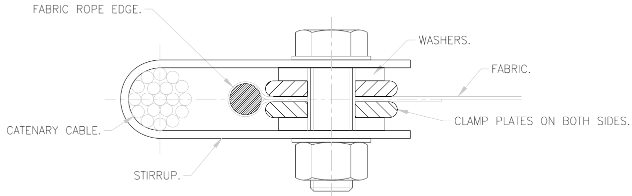


Fig 8: Typical Exposed Edge Cable Detail – IBP2 Entry Canopy, Jurong East

Fixed edges – The membrane usually has a thickened edge formed by sealing a polyester rope into a small pocket. This can then be fed into an aluminium extrusion or trapped between aluminium clamp plates and bolted onto supporting steelwork.

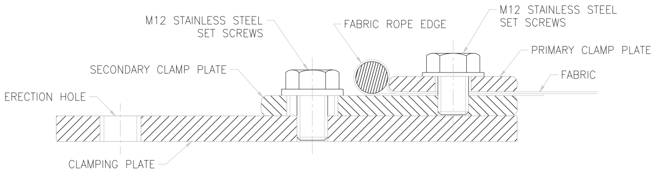


Fig 9: Fixed Edge Detail - Clamp Plates

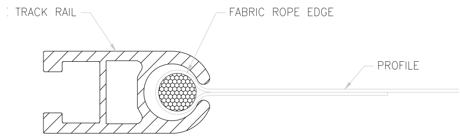


Fig 10: Fixed Edge Detail - Extrusion

Membrane Plates – These are typically used at corners of free form structures. The membrane plates collect the edge catenary cables and fabric onto the plate. In turn the plate can be pulled out to tension the structure with rigging screws, U-bolts or by shortening the support cables to the perimeter mast. It gives the structure a good deal of flexibility and tolerance.

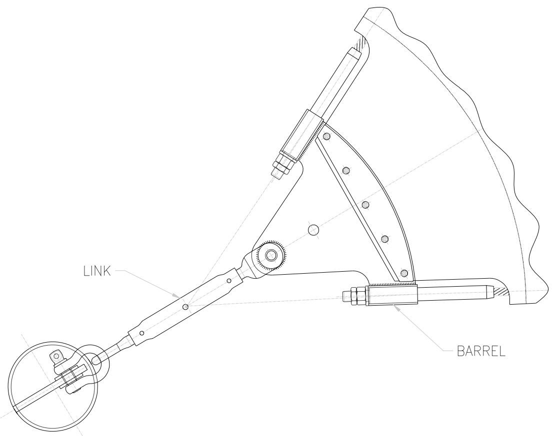
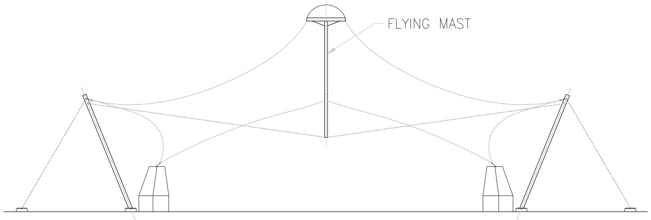


Fig 11: Typical Corner Membrane Plate Detail – Diving Pool Canopy, Changi Naval Base

Ring Beam & Masts – Conical canopies have central ring beams. These are usually supported by a mast. There are numerous ways of supporting the mast. One elegant way is with a flying mast supported with cables back to the perimeter. Conical canopies can be tensioned by jacking the ring beam up the mast, or jacking the mast itself.



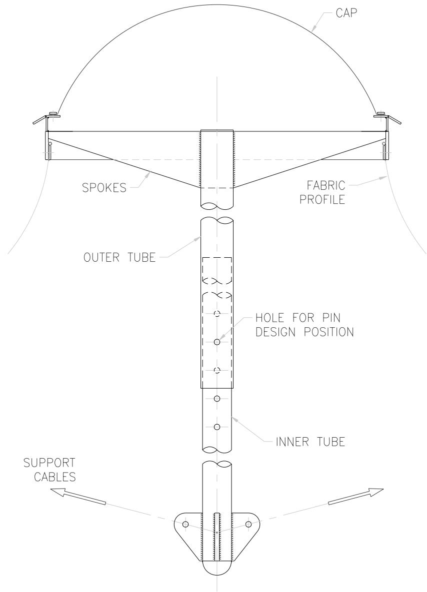


Fig 12: Section through Marine Crescent Conic

Fig 13: Typical Details of Flying Mast

Patterning

Efficient patterning of tensioned membrane structures requires examination and evaluation to:

1. Determine panel sizes and splice locations, in order to have the structure into manageable sized pieces for fabrication and installation.
2. Choose the most appropriate orientation of the clothes, to match the direction of principal curvature and have a smooth transition of the warp direction of the clothes.
3. Minimise the fabric wastage.

All fabric types stretch under load, although some exhibit different characteristics over time. A properly design tensioned membrane structure should take the stretch characteristics into account.

Each batch of fabric should be tested in a biaxial test rig to measure the stretch in both thread directions (warp and fill) at the stress ratios determined from the computer modelling. These figures can then be used to determine appropriate compensation factors to apply to the patterns. Thus the canopy is deliberately manufactured undersize so that when installed it tensions out to it's correct final dimensions.

Having considered all the parameters the cutting patterns can be produced using relevant computer software. To the basic pattern data the add-ons, match marks, bolt hole locations and reference data can be added, then sent for fabrication.

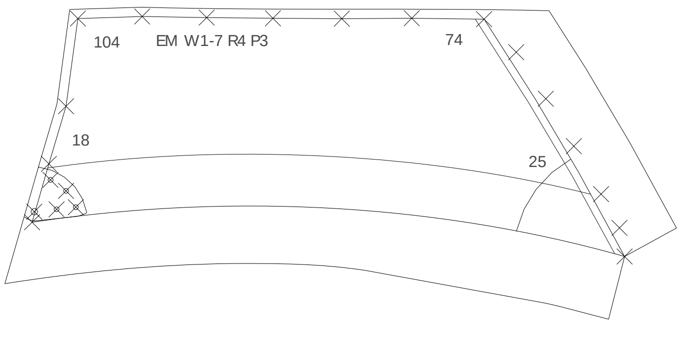


Fig 14: Typical Fabric Pattern – East Meadows Condominium Walkway

LSAA 2002 Proceedings