LSAA Technical Symposium

Design of Tension Shade Cloth Shade Structures

Engineering Design Factors

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Wade Design Engineers

Fundamental Concepts

- Membrane structures must be kept taut and free of wrinkles
- This is achieved by prestressing the membrane surface
  - Making it smaller than the final size
  - Design the shape to be "saddle shaped"
  - Design the support system to define the form
- Being able to determine cutting patterns well
- Having a good feel for loads and detailing
- Having the ability to make adjustments

The Membrane

- Multi-tasking element
  - Environmental barrier
    - Filters UV, controls lighting, water barrier, thermal properties
  - Flexible, prestressed, self supporting
  - Main loads are from prestress and wind (Australia)
- Typically are attached to more traditional support elements – cables, beams, masts, arches & rings

Inter related aspects of membrane structures.

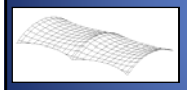
- Geometry
  - Aim for a "saddle shaped" surface
  - Traditional support elements have a geometry to achieve this anticlastic surface shape
- External Loads
  - Wind pressures – downwards & uplift, influenced by geometry
- Internal fabric stresses
  - Coupled with the saddle shape combine to resist external loads

Saddle shaped surfaces

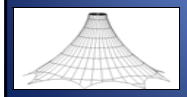
- Required / very desirable for all (anticlastic double curvature form) but "air supported" (synclastic form) structure

Surface Form Possibilities

– Hypar



– Barrel Vault

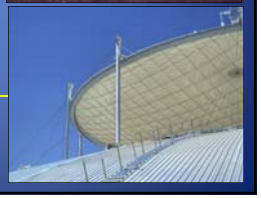


– Conic

Surface Form Possibilities

– Ridge valley system

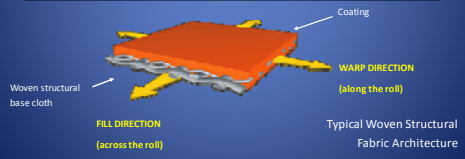
– Inflated



Choice of direction for seam lines

– Structural directions have two perpendicular directions
  - Along the roll – warp direction
  - Across the roll – fill / weft direction

– In most woven structural fabrics the warp direction is normally:
  - Stronger (tensile strength)
  - Stiffer
  - Less susceptible to creep

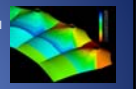


Typical Woven Structural Fabric Architecture

Level of pre-stress

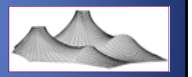
Shade cloth panels prestress may be 0.25 kN/m

– Form finding is concerned with the RATIO of the warp stress to fill stress, i.e, 1:1, 2:1, 1:2 etc.



– ACTUAL (theoretical) level of pre-stress in a fabric structure can be varied depending on requirements.

– Guidelines for minimum levels of pre-stress
  - PVC fabrics – 1.5 kN/m
  - PTFE fabrics – 2.5 kN/m



Ratio used during the shape finding process warp : fill	Typical level of pre-stress in the fabric in kN/m, warp : fill	
	PVC Fabric	PTFE Fabric
1:1	1.5 / 1.5	2.5 / 2.5
2:1	3.0 / 1.5	5.0 / 2.5
1:2	1.5 / 3.0	2.5 / 5.0

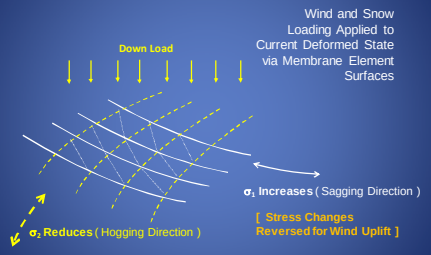
Level of pre-stress

– Advantages of a higher level of pre-stress:
  - Less chance of wrinkling on installed structure
  - Lower deflections under load
  - Less fatigue on support components (less movement / deflection)

– DIS-advantages of a higher level of pre-stress:
  - Higher overall membrane stresses
  - Higher forces in support structure, foundations etc
  - Increase in 'permanent' stresses in fabric and on the support components – possible reduction in lifespan.

– Choice of 'theoretical' pre-stress level

Load Analysis



Wind and Snow Loading Applied to Current Deformed State via Membrane Element Surfaces

σ_1 **Increases** (Sagging Direction)

σ_2 **Reduces** (Hogging Direction)

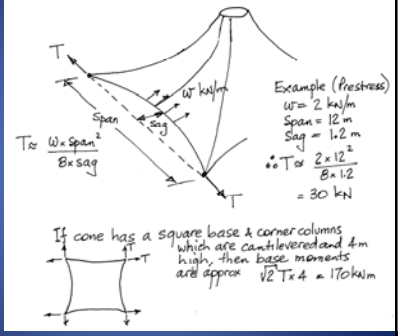
[Stress Changes Reversed for Wind Uplift]

Material Elastic Properties and Selfweight Introduced into Prestress Equilibrium Form

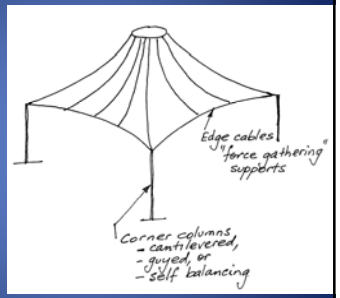
Typical Cone Structure

A little bit of maths gives us an idea of cable forces and hence support reactions.

("prestress only")

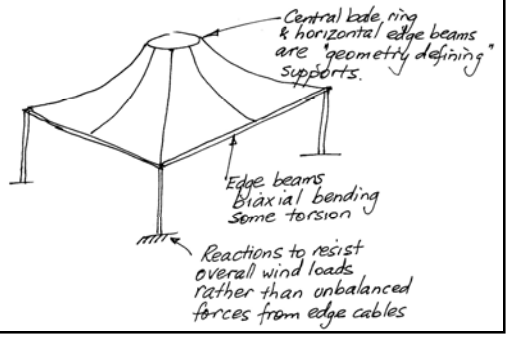


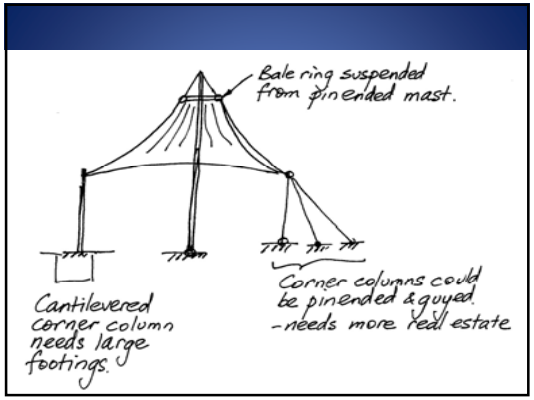
How do we resolve some of the loads generated?



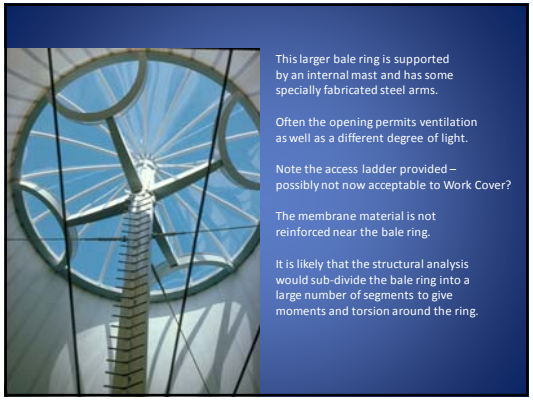
Typical small bale ring – 4 segments, 4 lifting points

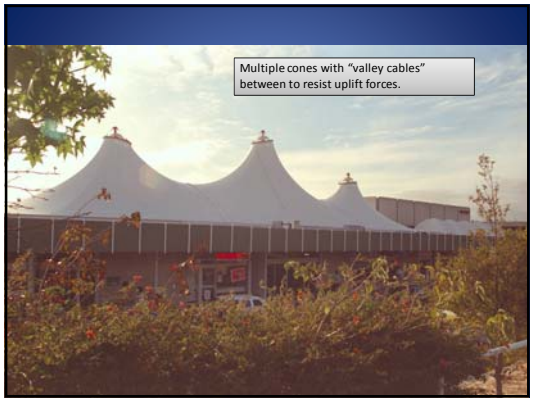
Fabric stresses will cause bending and torsion in the bale ring



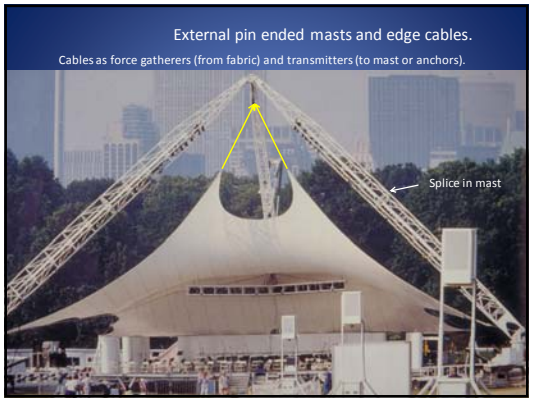

Bale ring suspended from pin ended mast.
Cantilevered corner column needs large footings.
Corner columns could be pinended & guyed -needs more real estate


This bale ring is suspended from above the structure
Note the fabric has been doubled up near the smallish bale ring. There has been a trend towards larger diameter bale rings to avoid reinforcing the fabric. Note the double curvature of the membrane surface – "anticlastic".


This larger bale ring is supported by an internal mast and has some specially fabricated steel arms.
Often the opening permits ventilation as well as a different degree of light.
Note the access ladder provided – possibly not now acceptable to Work Cover?
The membrane material is not reinforced near the bale ring.
It is likely that the structural analysis would sub-divide the bale ring into a large number of segments to give moments and torsion around the ring.

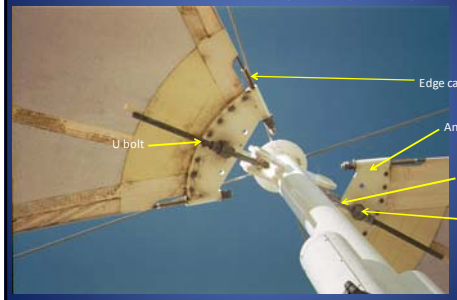

Multiple cones with "valley cables" between to resist uplift forces.


Twin cones with edge cables and corner loads "balanced" by opposing horizontal struts.


External pin ended masts and edge cables.
Cables as force gatherers (from fabric) and transmitters (to mast or anchors).
Splice in mast

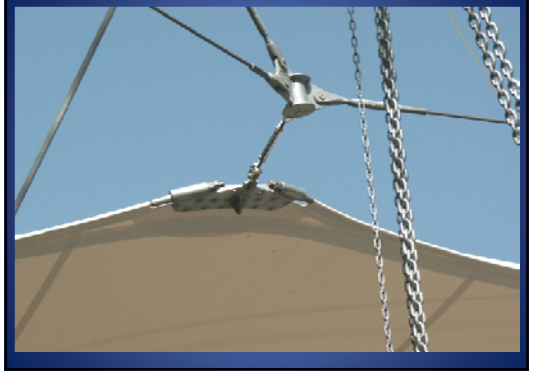
Arches form a common load carrying and geometry defining support.

Edge cables with swaged threaded ends allow for adjustment at corner anchor plates which in turn are attached to the column using U bolts and a large pin through the anchor plate.
The fabric is clamped to the top side of the plate.



An example of edge cables with threaded swaged ends and the use of a U bolt to adjust the position of the anchor plate relative to the mast.

An example of Exposed edge cable with U brackets. Usually on PTFE/Glass structures



A classic undulating "saddle-shaped" surface.

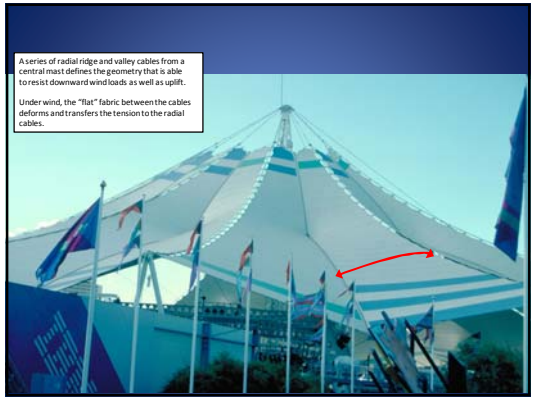
The size of the masts are greatly reduced by the presence of the top ring of struts.

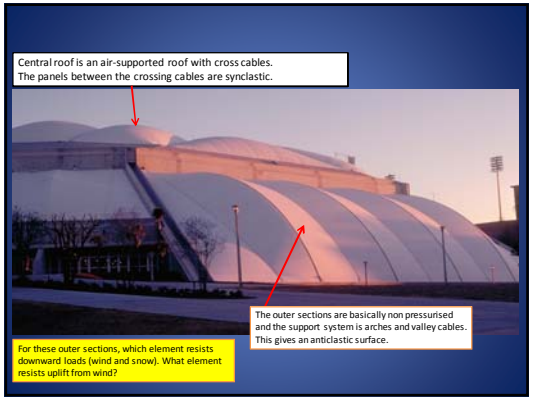
The "low" point attachments will generate considerable bending moments in those masts.

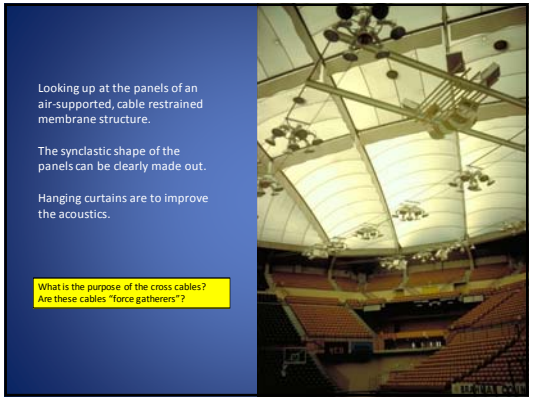
The opposing up & down fabric stresses can be appreciated in this structure.

An approximate "hand" analysis might assume that the vast majority of downward wind loads are resisted by the high points.

Any uplift might be assumed to be taken by the low points.


A series of radial ridge and valley cables from a central mast defines the geometry that is able to resist downward wind loads as well as uplift.
Under wind, the "flat" fabric between the cables deforms and transfers the tension to the radial cables.


Central roof is an air-supported roof with cross cables.
The panels between the crossing cables are synclastic.
The outer sections are basically non pressurised and the support system is arches and valley cables. This gives an anticlastic surface.
For these outer sections, which element resists downward loads (wind and snow). What element resists uplift from wind?


Looking up at the panels of an air-supported, cable restrained membrane structure.
The synclastic shape of the panels can be clearly made out.
Hanging curtains are to improve the acoustics.
What is the purpose of the cross cables? Are these cables "force gatherers"?


Base of pin-jointed mast may be designed to be jacked so as to prestress the entire membrane surface.


Splices can be designed to remain within the external diameter of the section


"Flying masts" are often used to enable smaller panels to be combined to cover a wide space.
Or, to enable higher local curvatures in the panels.
Aesthetics might be improved with a "modular" design.

Available Options for Panel Edge Tensile Members

Edge Cables in pockets

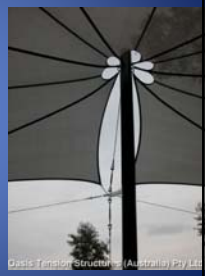
Similar detailing to solid fabric structures – need to stop fabric creeping away from the corners.

Discrete cables (Stainless) for each panel edge with adjustments
Continuous cable around panel – with clamps and adjustment.

Webbing

Commonly used in shade structures utilizing knitted shade cloth

Webbing sewn into the cloth transfers the fabric stresses to the cable/webbing



Structural Cable Basics

Having established the application, load requirements and desired level of corrosion protection, consideration should be given to:

1. Cable Construction.
2. Cable Termination Methods.
3. End Fitting Options.
4. Connections, Clamps, anchors and associated fittings.

1. Cable Construction - Options

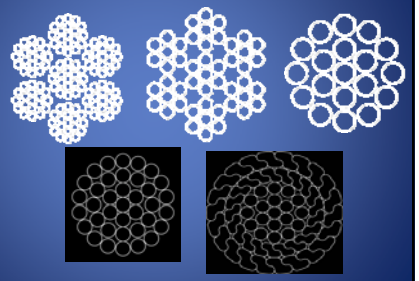
7 X 19
wire rope

7 X 7
wire rope

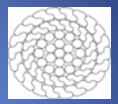
1 X 19
strand

1 X 31
strand

VVS-3
Full locked cable



1. Cable Construction – Strand / Full Locked



Open Spiral Strand (OSS)

- Wire-Ø up to 5 mm
- Construction 1x19, 1x37, 1x61, 1x91
- E-Modulus 150 (130) ±10 kN/mm2
- Diameter 3 to 36 mm
- No closed section of the cable
- Galvanized wires/GALFAN+stainless
- Socketing and swaging possible
- Back stays
- Main and Tension cables
- Hanger Cables
- Support cables
- Handrail cables

Full locked cables (VVS)

- Wire-Ø up to 7 mm
- Constr.: Z-profiled outer layer
- E-Modulus 160 ±10 kN/mm2
- Diameter 20 to 156 mm
- Closed (locked) section of the cable
- Wires galvanized or GALFAN
- Only socketing possible
- Bridge cables
- Back stays
- Main and Tension cables
- Support cables

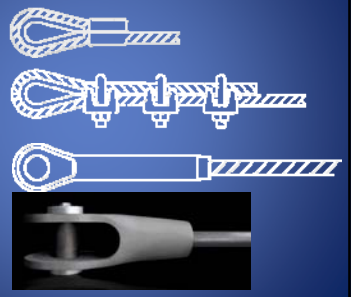
2. Cable Termination Methods

Swaged Ferrule eye

Wire rope grips

Swaged terminal end

Socket End.



3. End Fitting Options

Parameters for Designing Connection Assemblies

- 4 Main Parameters - Performance, Cost, Constructability, Aesthetics.
- Will the connection be subject to:
  - extensive movement
  - out of plane movement
  - vibration
  - repeated assembly/disassembly?
- Will the connection be subject to extreme environments?
- What amount of rotational freedom is required?
- Design loads and safety factors need to be considered.
- Is the structure permanent or deployable?

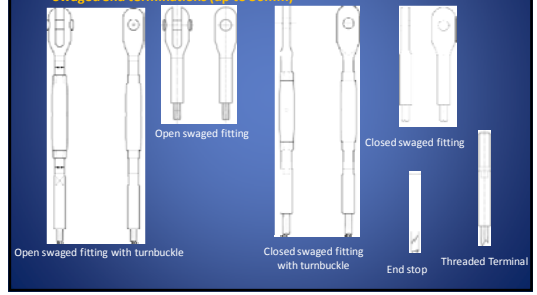
3. End Fitting Options

Each cable is only as good as the weakest fitting or connection!

- Must transfer the load from and to the cable.
- Must not add to fatigue.
- Must match the corrosion protection system of the mating/surrounding structure.

3. End Fitting Options

Swaged end terminations (up to 36mm)



3. End Fitting Options

Swaged end terminations - Compact Adjusters (Turnbuckles)

Features;

- *Wire diameters of 4mm to 22mm*
- *Sleek minimalist look, compact and perfectly suited for architectural applications*
- *Full adjustable telescoping fitting*
- *Recessed clevis pin positively secured with circlips*

Cable Diameters:
4mm through to 22mm

Applications;

- *Used for highly visible applications of moderate adjustment*
- *Static applications where terminations are aligned*

3. End Fitting Options

Swaged end terminations - Turnbuckles (Full Adjustment)

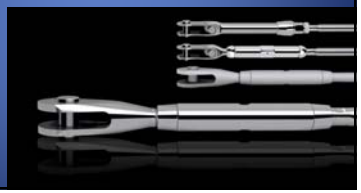
Features;

- *Wire diameters from 3mm to 36mm*
- *Fully adjustable cables offering increased adjustment*
- *Simple easy connection via clevis pins*
- *Type 1 and Type turnbuckles have toggles allowing for misalignment of cleats and aid in relieve stresses caused by dynamic loads*
- *All turnbuckles have lock nuts to positively lock adjustment*

Cable Diameters:
3mm through to 36.5mm

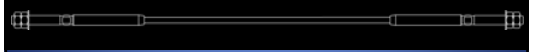
Applications;

- *Structural applications where maximum adjustment from a single end is required.*



3. End Fitting Options

Swaged end terminations - Threaded Ends



Features;

- *A choice of either Stainless or Galfan coated mild steel*
- *Diameters from 3mm and up to 36mm*
- *Simply easy tensioning*
- *Threaded ends can be secured by either plates or threaded anchorages (can be internal)*
- *Cable terminations must align and be accessible*

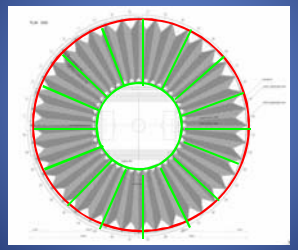
Cable Diameters:
3mm through to 36.5mm

Applications;

- *Simple effective tendons for non loaded adjustment*

Stainless Cables – Swaged End Terminations

The Spoke Wheel



Cable Design Basics

Tension Only

- Cables only work in tension.
- Perpendicular loads can only be taken with large deformation.

- Deformation can be limited by pre-stressed systems.

Cable Design Basics

Rules for Cable Structures

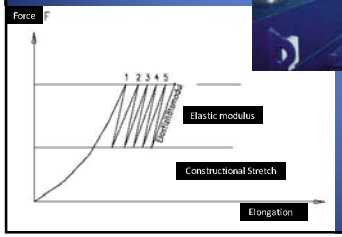
1. Cable structures tend to have large deflections / movement
2. Deformation can be limited by pre-stressing the cable system
3. Avoiding movement or deformation will lead to oversized / uneconomic structures – definitely not lightweight!!

Design for flexibility, use hinges and allow for large movements

Cable Length

Cable Creep

Pre-stretching/elongation after multiple loadings



Cable Length

Cable Elongation (Strand Modulus)

$$\Delta L_{elast} = (F_{sys} * L_{sys})/(E*A)$$

L_{elast} :	Elastic elongation
F_{sys} :	System force of the cable (structural analyses)
L_{sys} :	System length of the cable
E:	Modulus of elasticity
A:	Metallic cross section

Software

- Formfinding functions – shape to change to suit prestress and support locations
- Wind loading and load-deflection of fabric
- Tension only elements (slack cables, fabric wrinkling)
- Large deflection capability
- "Extras" – patterning, shade prediction, drainage, ponding, heat loads, rendering for architectural considerations

Large wind deflections (15 m/sec)

Abrasion with supporting arches and shock loadings onto attachments to buildings etc

Hail Loads (next day !!)