An Introduction to Tension Fabric Structures

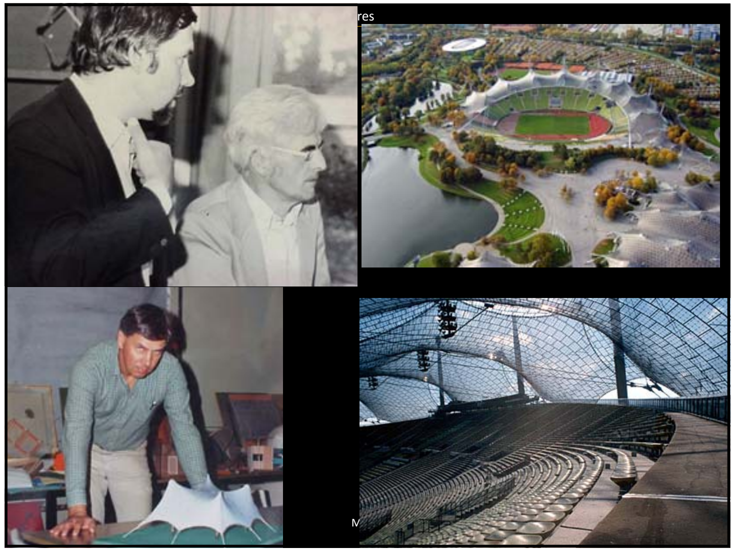
LSAA Presentations
Peter Kneen, Bob Cahill, Peter Lim
LSAA-MADA Workshop Resource 2016

Introduction & Brief History of Tensile Structures

Introduction

- “Tension Fabric Structures” Presentations by the LSAA
- About the Lightweight Structures Association
- Main Topics to be covered
  - History & Fundamentals
  - Textile materials
  - Structural supports
  - Design principles and procedures
  - Fabrication, assembly and erection procedures

The Birth of the MSAA 1981 / LSAA



Introduction to Membrane Structures

Lightweight Structures Association of Australasia

- The aim of LSAA is to promote proper design and application of lightweight structures including:
  - Tension Fabric Structures – “solid” and “open” fabrics.
  - Cablenet and cable supported structures.
  - Shell and folded structures, Space grids.
  - High Tech Glazing systems.
  - New forms of large span, energy efficient or sustainable construction

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Introduction to Membrane Structures

About the LSAA

- Founded as the MSAA in 1981 when membrane structures were being established in Australia / NZ
- Members: Engineers, Architects, Fabricators, Contractors, Suppliers, Students
- Holds Conferences and Symposiums
- Holds LSAA Design Awards every 2 years
- NFP organization run by elected committee supported by a part time EO.
- Website: www.LSAA.org

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Development of Modern Fabric Structures
• Pioneered by Frei Otto in 1950s,
eg, Dance Pavilion in Cologne (1957)
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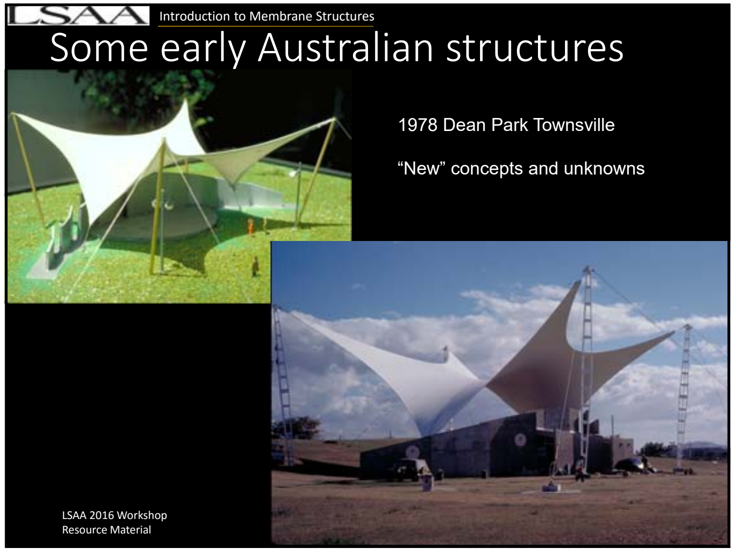
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Some early Australian structures
1978 Dean Park Townsville
"New" concepts and unknowns
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Air Supported
Used for many outdoor pools for a while in the 1980s
Burswood (Perth) only cable restrained air dome in Australia
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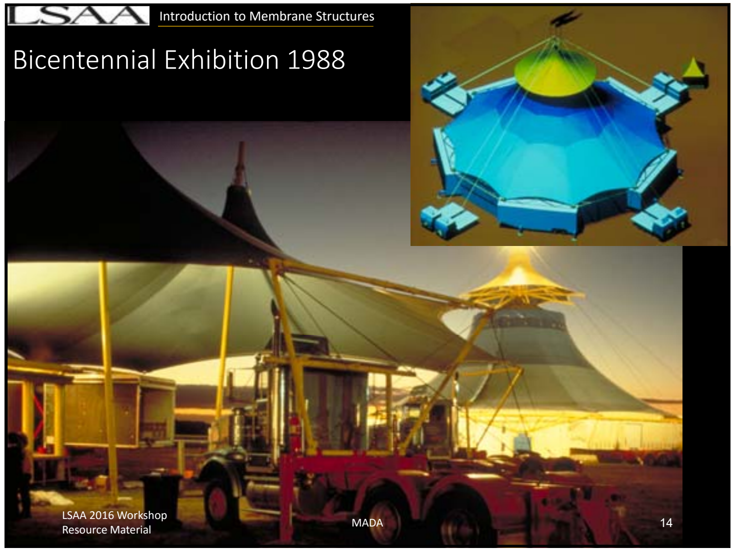
Expo 1988 Brisbane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Bicentennial Exhibition 1988
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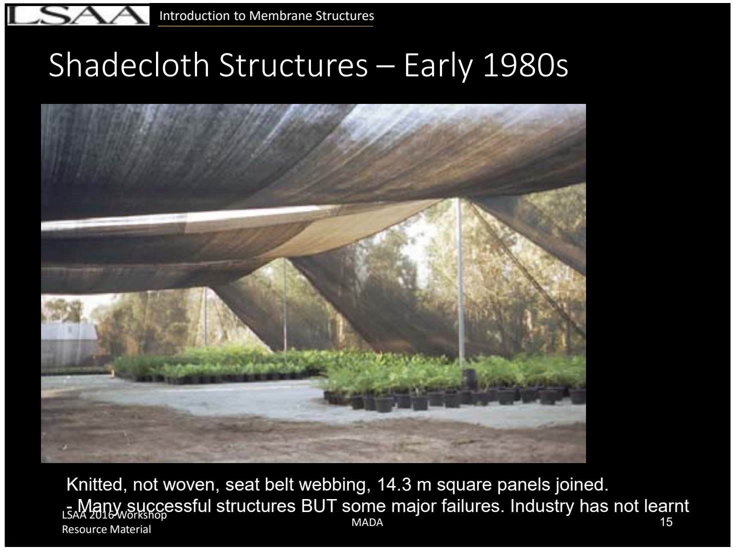
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Shadecloth Structures – Early 1980s
Knitted, not woven, seat belt webbing, 14.3 m square panels joined.
- Many successful structures BUT some major failures. Industry has not learnt
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Superspan
Prototype 1982
4x2 Panels (14.3m square)
With / without wall panels
Observed under winds for 4 months
Uplift forces and deflections recorded.
70% shade factor, knitted, webbings

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Green Scene - Victoria

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Car Storage Yards

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Part of the current interest

Structural Elements & Actions

- Cables, ropes, rods – tension (efficient)
- Columns, struts – compression (OK but buckling)
- Beams – bending (inefficient)
- Slabs – bending (inefficient)
- Walls – compression, shear
- Trusses – “efficient beams” but costly to make

Some Traditional Structures

- Roofs – loads applied to metal decking to purlins to trusses or portal frames and down to foundations. Mainly by bending.

- Floors – loads applied to slabs hence by bending / shear to isolated edges beans and then to columns.
  [or floor boards to joists to bearers to main beams to piers etc]

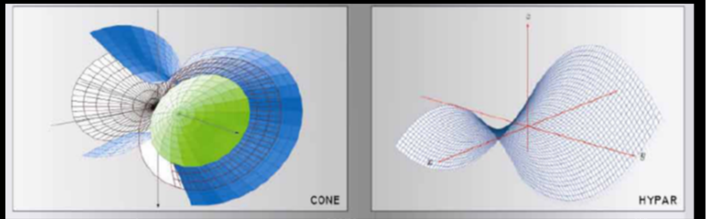
Examples of Efficient Structures

- When the traditional methods become too expensive and there is some architectural freedom in terms of geometry
  - Arches, Suspension cables, Domes, shells

- Tension Fabric Structures are efficient for increasing spans with proper engineering design and understanding the materials

What is a Tension Membrane Structure?

- Resists applied loads by tensile actions –and hence makes an optimum use of material
- Needs a level of pretension for geometric stability
- Often doubly curved in space (saddles and cones)



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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

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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

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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

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Saddle shaped surfaces

- Required / very desirable for all but "air supported" structures.

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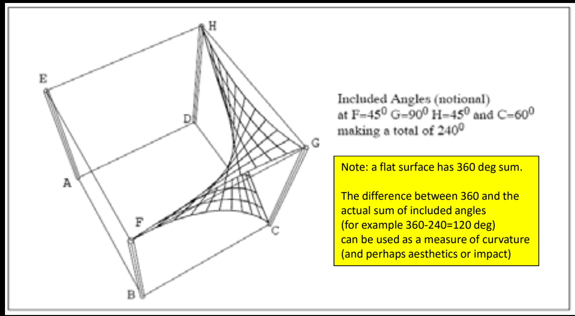
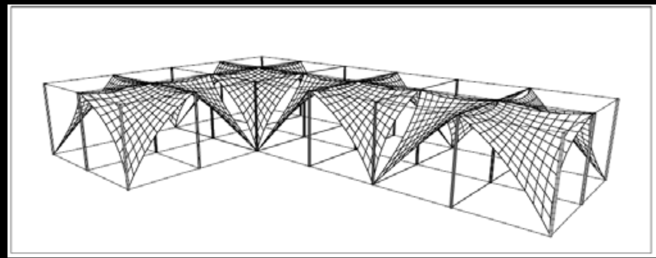




Multiple simple modules of the same panel can be used for an improved overall impact.

A look at a PVC cone structure

- Components (fabric, cables, columns, bale ring)
- Fabric prestress (want fabric to remain taut)
- Forces generated (in cables, columns etc)
- Resisting the forces (different means)
- Engineering – Peter Lim
  - Basic geometry aspects
  - Formfinding, structural analysis
  - Patterning

Typical Cone Structure

Reg 90 kg Garry 110 kg Terry 85 kg Joan 70 kg Lyn 75 kg

Total = 430 kgs = 4.3 kN approx.

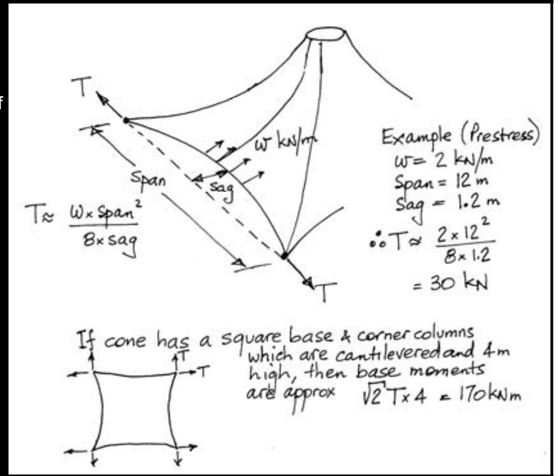
Spread over 4 – 4.5 metres

= say 1 kN/m

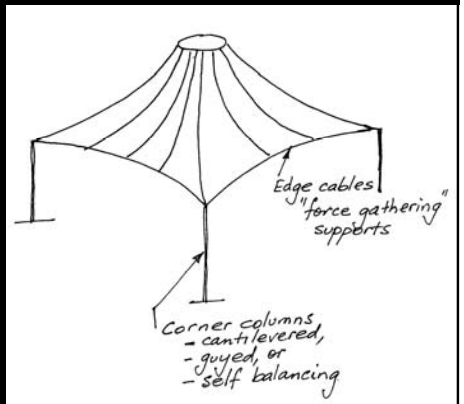
Fabric prestress (small PVC cone) say 1 kN/m to 2 kN/m

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

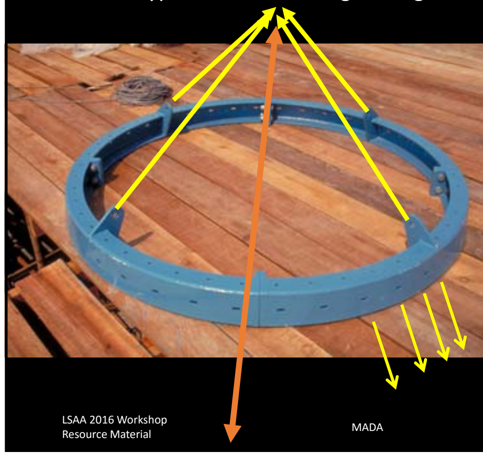
("prestress only")



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

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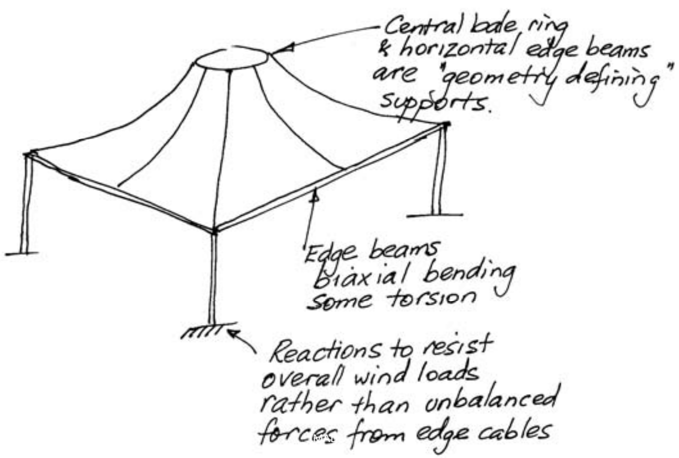

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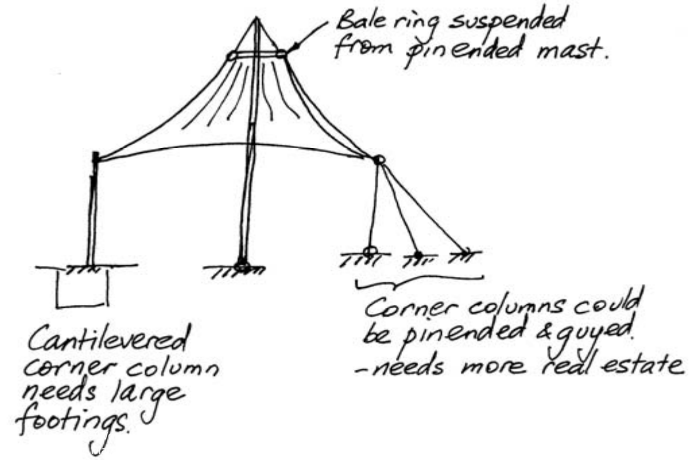

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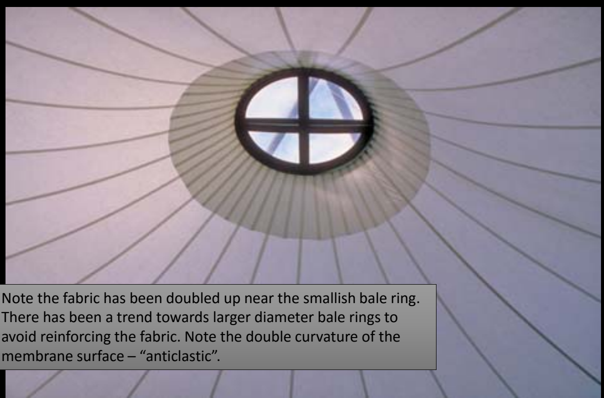
This bale ring is suspended from above the structure



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".

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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.


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Multiple cones with "valley cables" between to resist uplift forces.
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Twin cones with edge cables and corner loads "balanced" by opposing horizontal struts.
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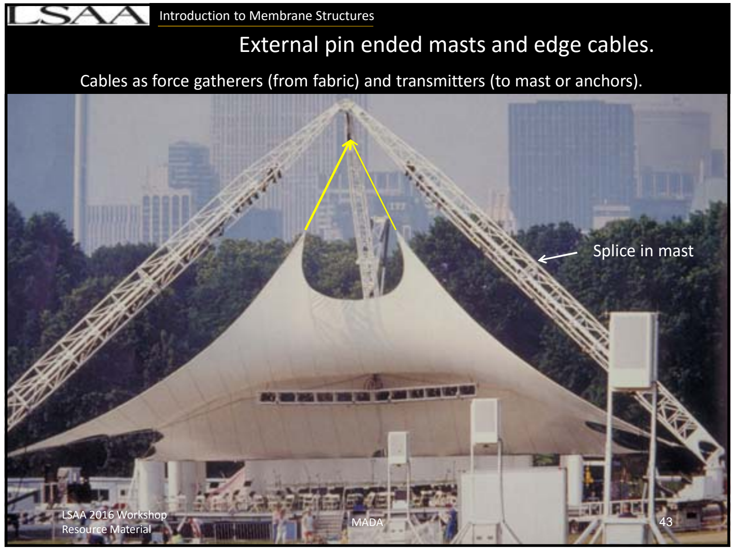
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External pin ended masts and edge cables.
Cables as force gatherers (from fabric) and transmitters (to mast or anchors).
Splice in mast
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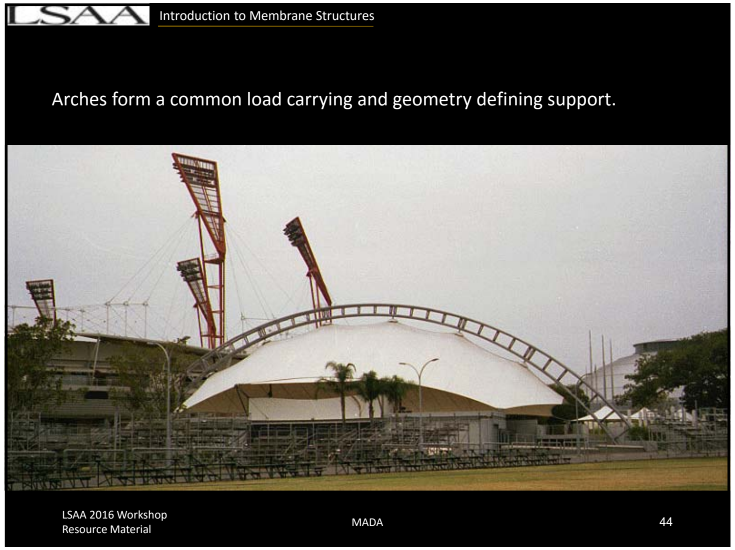
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Arches form a common load carrying and geometry defining support.
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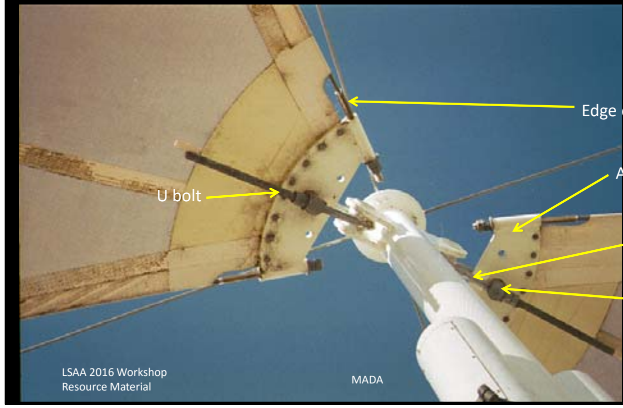
Edge cables with swaged threaded ends allow for adjustment at corner anchor plates which in turn are attached to the column using U bolts and a large pin through the anchor plate.
The fabric is clamped to the top side of the plate.



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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.

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Main Lecture Topics

- Materials - Textile Options
- Membrane Structures – Fundamentals
- Support Structures – Hypars & Cones
- Cables and Other Support Details
- Design Processes
- Fabrication and Installation

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Introduction to Membrane Structures

Textile Materials for Architectural Structures

Bob Cahill – LSAA, STA

Overview

Architectural fabrics are playing an increasing role in the Australian and global built landscapes.

Textile clad light structures deliver superior design, aesthetic, cost and build time advantages over traditional construction forms.

In a world where Environmentally Sustainable Design and Embodied Energy are fast becoming the key driving forces of modern Architecture these benefits are now more compelling than ever.

Overview (cont...)

Fabrics facilitate advances in architectural design by virtue of:

- Environmental Sustainability
- Energy Efficiency
- Structural Strength
- Cost Efficiency
- Aesthetic Effects
- Low Maintenance
- Space Extension

- Longevity
- Durability
- Flexibility and Portability
- High Performance
- Shade and Light Diffusion
- Extreme Temperature Resistance
- Flame Retardancy

Infinite Variety

Structures can be created in a variety of forms, sizes, spans, colours and even graphically printed giving infinite variety and freedom of creativity.


Manama - Bahrain


Shopping centre Plymouth - UK

Limitless Applications

From stadia to a school yard, from desert to the arctic no application or environment is beyond the scope of Architectural Textiles.


Faro stadium - Euro 2004 Portugal


Lesigny - France


Beckham Academy London

Limitless Applications

From stadia to a school yard, from desert to the arctic no application or environment is beyond the scope of Architectural Textiles.

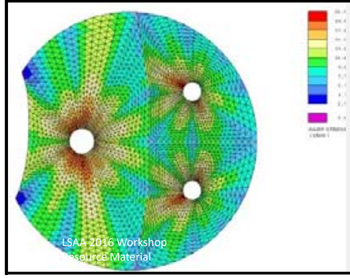
Grand Canyon view point USA

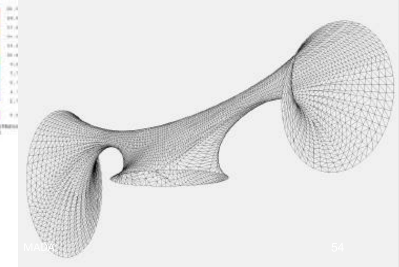
Inflatable dome Kuopio - Finland

Specialist Engineering Input

Architects and Engineers are exploring the many non-linear relationships in designing tension structures. The relationship between panel patterning and the desired shape is critical.

Expert modelling and engineering is needed to manage the complex changes in dimensions across membrane panels due to tension curvature and the inherent behaviours of different textiles.





Textile Selection

There are diverse forms of architectural textiles. Selection criteria relates to:

- Suitability for Structure Function
- Wind Load Resistance
- Life Cycle Expectations
- Design Expression and Aesthetics
- Desired Level of Light Transmission
- Desired Level of Solar Heat Gain
- Building Codes
- Economics – Relative Costs
- Maintenance
- Waterproofness

Most Architectural fabrics offer warranties and life spans exceeding performance expectations

Types of Fabrics

Today we focus on five preponderant types of architectural textiles:

- P.T.F.E. Polyethylene Tetrafluoride on Fibreglass base fabrics (“Teflon coated fibreglass”)
- P.V.C. / P.V.D.F. / P.E.S. Polyvinylchloride with Polyvinylidene Fluoride on Polyester base fabrics
- E.T.F.E. Ethylene-tetrafluroethylene (“Foils”)
- H.D.P.E. Shadecloth High Density Polyethylene
- Silicone Coated Fibreglass We will not cover this type of material

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1. PTFE “Teflon coated glass”

Skilled Park Gold Coast
Queensland

Introduction to Membrane Structures

1. PTFE “Teflon coated glass”

Millennium Dome London

Introduction to Membrane Structures

1. PTFE

- Manufactured by coating woven fibreglass yarn with a PTFE emulsion.
- The heavy grade fibreglass used is stable, non-combustible and resistant to chemicals and UV light.
- Provides a high level of light diffusion.
- Forms a weather-tight barrier.
- PTFE is chemically inert.
- Possesses high tensile strength and has good dimensional stability.
- Highest cost balanced by highest durability and longest life.
- Not yet recyclable.

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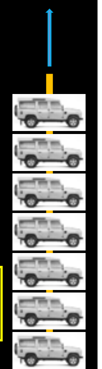
PTFE CHARACTERISTICS (typical)

Weight	1380 gsm
Thickness	0.8 mm
Tensile Strength	450 daN / 3cm
Elongation	10 %
Light Transmittance	11 %

450 daN/3cm equates to 15 tonnes of tension per metre
- For a fabric less than 1 mm thick and weighing 1.4 kgs / sqm

1 metre width of fabric 1mm thick can carry 7 empty Defenders



PTFE generally regarded as the “top of the range” fabric

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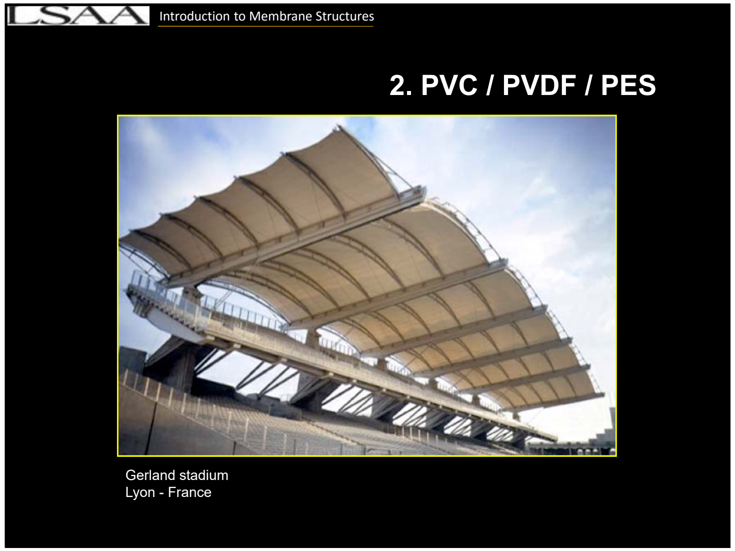
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2. PVC / PVDF / PES
Gerland stadium
Lyon - France


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2. PVC / PVDF / PES
Hotel Foyer
Cairns
F1 Kuala Lumpur - Malaysia
Lake Pontoon
New York state
Rio de Janeiro -
Brazil


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Australian Textile projects
win worldwide recognition
Port Douglas Sailmakers - Cairns
Shade to Order - Newcastle Airport
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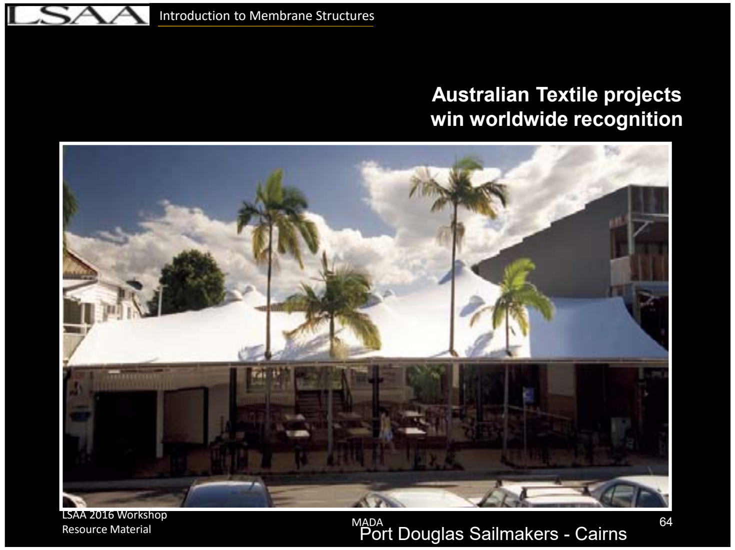
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win worldwide recognition
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Port Douglas Sailmakers - Cairns

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Exporting Australian Textile skills – Mumbai Airport -Makmax

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2. PVC / PVDF / PES aka PVC composite

- PVC – long chain polymer with chloride molecules attached.
- PVC is the most widely used plastic in the world after LDPE.
- PVC fabric production consists of multiple coatings: Adhesives, Primers, main coat of PVC on a high tensile polyester fabric with a top coating of PVDF.
- Some European mills also 'top'-coat the under-side of the fabric in PVDF.
- Polyester base cloths offer strength, durability and low shrinkage.
- The PVC protects the polyester from aggressive UV and adds aesthetic qualities and flexibility.
- PVDF top coatings improve cleanability and longevity.
- Attractively priced and easy to fabricate. Fully recyclable.

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TYPICAL PVC TEXTILE CHARACTERISTICS BY CLASS

Class	Weight	Tensile Strength	Tear Strength	Coating
Type 1	650-900 gsm	300/280 daN/5cm	30/28 daN	PVC PVDF
Type 2	900-1050 gsm	420/400 daN/5cm	55/50 daN	PVC PVDF
Type 3	1050-1350 gsm	560/560 daN/5cm	80/65 daN	PVC PVDF
Type 4	1350-1500 gsm	800/700 daN/5cm	120/110 daN	PVC PVDF
Type 5	>=1500 gsm	1000/800 daN/5cm	160/140 daN	PVC PVDF

Architectural Grade PVC textiles conform to World Fire Retardancy Standards including AS 1530

1000daN/5cm equates to 20 tonnes of tension per metre – Type 5
Type 2 approx 8 tonnes / metre

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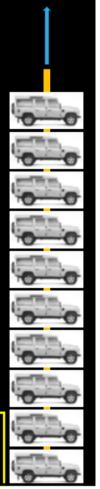
1 metre width of Type 5 fabric approx 2mm thick can carry 10 empty Defenders



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3. ETFE

Clarke Quay
Singapore

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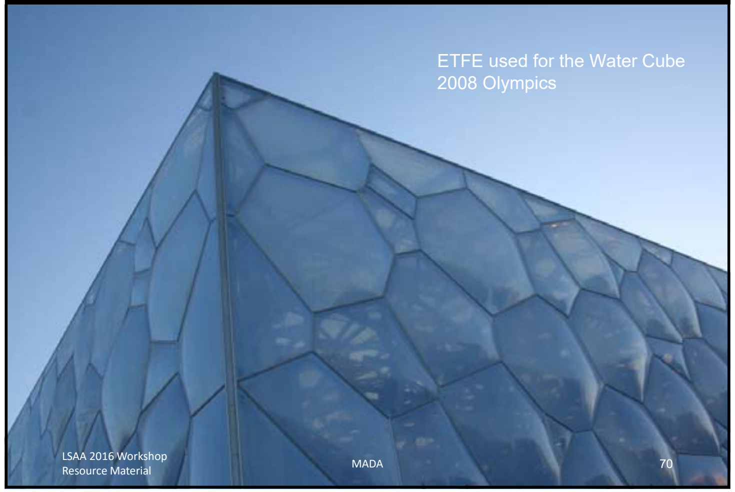

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3. ETFE “Foils / Film”

- A high performance lightweight film manufactured by extrusion technique
- Transparent, Durable, Flexible, Self Cleaning, Non Adhesive, Energy Efficient.
- Landmark Projects: Beijing Watercube (2008 Olympics), Munich’s Allianz Arena (2006 World Cup).
- Invented in 1970’s by Dupont.
- Estimated to be 30% more energy efficient than traditional glass.
- 1% the weight of glass with the ability to support 400 times its own weight
- Recyclable, with an expected life of 20 + years.
- Low emissivity with the ability to select levels of light transmission.

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ETFE FILM CHARACTERISTICS

Weight	Thickness	Tensile Strength	Elongation	Light Transmittance
175 To 438 gsm	100um to 250um	>=45Mpa	>= 400%	90 %

At 45 Mpa, 1 metre width of 0.1 mm thick foil can carry 4.5 kN. This restricts applications to smaller spans (small radius of curvature as per the “bubbles” of the Watercube).

Many applications use air inflated “pillows” of ETFE (like the “watercube” in Beijing) that contribute enormously to the thermal insulation of buildings and lighting qualities with significant savings in energy costs over the lifetime of the buildings.

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4. HDPE Shadecloth

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Knitted Shadecloth

- Shadecloth is a light weight industrial textile commonly used for outdoor protection. It uniquely offers a combination of UVR protection with a breathable finish providing an ideal cover for the harsh Australian environment.
- Commercial shadecloth is manufactured by knitting high density polyethylene. This is generally UV stabilised yarn that has exceptional tensile strength.
- Woven shadecloth is no longer used in structures.

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HDPE CHARACTERISTICS (typical fabric 200gsm)

	WARP	WEFT
Breaking force	80 daN /5cm	215 daN /5cm
Breaking extension:	84 %	63 %
Tear resistance:	17 daN	28 daN
Bursting force (Steel Ball):	mean 1861 N	
Bursting Pressure:	mean 3000 N	

80 daN/5cm is equivalent to 16 kN/m or a small car

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HDPE Knitted Shadecloth

- Knitted from filaments of High Density Polyethylene.
- High UV performance coupled with high tensile strength.
- Rachel knit (lockstitch) construction provides resistance to tearing and fraying.
- Ideally suited to moderate tension, modular shading applications requiring light-weight materials.
- Often used with sewn on edge "seat belt" webbing.
- Finds service in a wide variety of shading applications.
- Flexibility through wide width and broad colour range.
- Lowest cost BUT with proper engineering input still needed.

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3 Construction Methods used

- 100% Monofilament
  - Commonly used in the manufacture of heavy duty shadecloth. Typically has exceptional tear and tensile strength.
  - Can be very heavy when installed over a large span requiring additional tensioning
  - Depending on the knit will generally have low UVR block levels
  - Typical applications: Car parks and large commercial structures

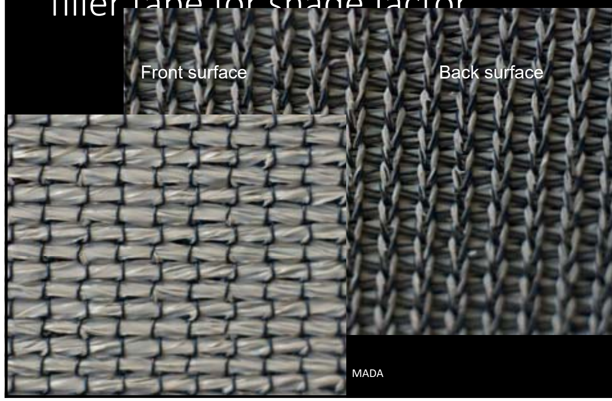
3 Construction Methods used

- Monofilament and Tape
  - Most common type of manufacturing method
  - Tape insert provide high levels of UVR block
  - Monofilament provide strength while tape insert provides increased UVR block. Tape provides no strength.
  - Monofilament is HDPE and tape is LDPE
  - Typical applications: Schools, playgrounds and domestic shade sails

3 Construction Methods used

- Monofilament with oval monofilament insert
  - Recent technology proving to be effective.
  - Provides exceptional strength and high UVR block
  - Heavy weight product

Cloth construction – lock stitch with filler tape for shade factor



Polyethylene Yarn

- High-density polyethylene has a linear structure which provides better tensile properties – the result is a stronger yarn and stronger shadecloth
- Polyethylene has a high strength to weight ratio and does not absorb liquid – greater stain resistance.
- Polyethylene is affected by ultra-violet light however UV stabilisers are used to prevent UV degradation.
- UV stabilisers can be affected by halogens (e.g. Chlorine, Bromine, Iodine, Fluorine).
- Flame retardants are added to polyethylene to improve the flame retardancy characteristics of the yarn.

Threads

- Thread is a relative low cost item used in the fabrication of shade sails yet it is often overlooked as an integral part of a successful installation.
- There are 3 common types of thread available
  - Polyester/Cotton blended thread
  - Polyester thread
  - PTFE thread

Characteristics of Threads

- Polyester/Cotton Threads
  - Typically used in upholstery and trim
  - Not compatible with extended UVR exposure
  - Not recommended for shade sails
-
- Polyester thread
  - Good initial strength and reasonable UVR expectancy
  - Can be solution dyed providing excellent colour-fast characteristics

PTFE Thread

- Similar initial strength to Polyester however it does not degrade over extended periods of UVR exposure hence extended manufacturers warranties
- Very expensive thread but still relative low in the overall fabrication of a shade sail or structure
- Fast becoming the product of choice for large shade sails fabrication

Sewn connections used for attaching (possible) edge webbing "cables"
Local corner attachment reinforcement
Edge pockets and joins in rolls of shadecloth

Good fabrication practices, quality control are important as the choice of thread.

Webbing

- "Shade Sail Webbing" generally has the following characteristics:
  - Width: Commonly 50mm
  - Installations: Typically used on a smaller shade sails around the perimeter for reinforcing however some fabricators use webbing in the perimeter pocket instead of a stainless steel cable.
  - Made form 100% Polyester – stretches to about 10%
  - UV Stabilised
- Webbing sewn splices need to be tested

Edge Cables and Attachments

- For shade cloth panels
  - Use standard stainless steel cables and fittings
  - Need adjustments for length on cables
  - Prefer use of swaging to wire rope clamps

Materials - Conclusions

- Need to have a knowledge of the types of fabric and shadecloth
- UV protection in coatings or the yarn/filament for shadecloth
- Don’t skimp on threads, webbing, seams

Textile Materials - Summary

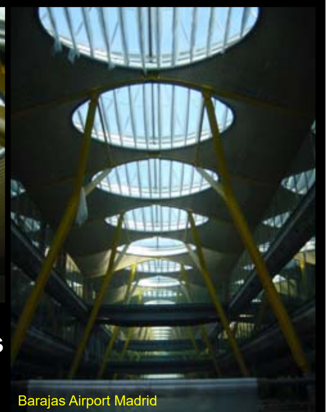
- We have presented only a modest sampling of the extraordinary scope of Architectural textiles.
- We saw that matching the appropriate Architectural textile to a given project is multi criteria dependant
- Textile structures present compelling evidence of the enhancement potential for built landscapes based on cost and time efficiencies as well as social and environmental benefits.

Knitted Shadecloth Structures

- Knitted cloth has eliminated woven shadecloth since mid 1980s
- Early applications were bird, frost, shade and hail protection for nurserys
- Modular panels were also used for large car storage yards (hail, sun)
- Discontinuous panels now common in car dealers, shopping centre parking areas, council playgrounds, schools and domestic applications.
- Edge conditions can be sewn webbings, stainless steel wire ropes in pockets.
- These structures have the highest rate of failures (complete or partial) causing the greatest concern for the industry. Loadings, shaded area and deflections are often underestimated and competent engineering is often absent.


Barajas Airport Madrid

5. Silicone Coated Fibreglass


Barajas Airport Madrid

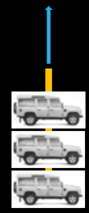
Silicone Coated Fibreglass

- Woven glass fibre with specially formulated translucent or pigmented silicone elastomer coating.
- Product still in evolutionary development phase.
- Range of weights to suit various applications.
- Flame retardant (non-combustible), non-toxic, hydrophobic and UV filtering.
- High temperature resistance (-60˚C to +400˚C)
- To date, primarily suited to interior applications.

SILICONE COATED TEXTILE CHARACTERISTICS

Weight	Tensile Strength	Tear Strength	Light Transmittance
260 gsm	300daN/5cm	60 / 60daN	50 %

300 daN/5cm is equivalent to 60 kN/m or 3 empty Defenders.



Questions ?

End of session – chance to visit the Trade Exhibits – perhaps seek out material suppliers for information.

Introduction to Membrane Structures

Applied Loadings & Engineering Design Factors

Peter Lim, Tensys, VP LSAA

Introduction to Membrane Structures

Australia – Main Loadings

- Initial prestress
  - Fabric made smaller and needs to be stretched to fit supports
  - Always present
  - Often insufficient particularly shadecloth applications
- Wind loads
  - Major load, any direction, UP and DOWN
- Hail and rain
  - Ponding, drain blockage, HUGE problem for shadecloth structures
  - Geometry & prestress for PVC, PTFE structures can avoid this
- Erection
  - Lifting large unrestrained areas, manpower and equipment studies

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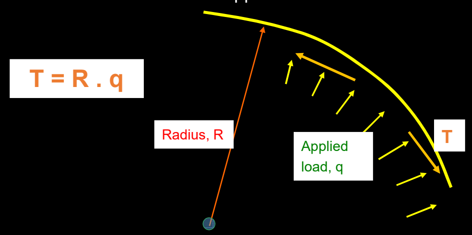
Introduction to Membrane Structures

Membrane form finding

"THE SHAPE AND CURVATURE OF THE MEMBRANE DEFINES ENTIRELY HOW THE STRUCTURE WILL CARRY LOAD"

- Form finding is the first stage of any tensile structure analysis
- There is one basic equation which describes the behaviour of all tensile structures:

Membrane stress = Radius x Applied load



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Introduction to Membrane Structures

Surface Form Possibilities

- Hypar
- Barrel Vault
- Conic

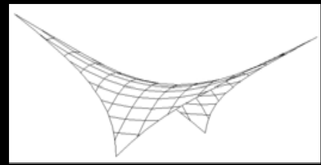
Introduction to Membrane Structures

Surface Form Possibilities

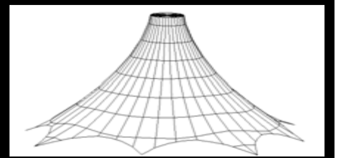
- Ridge valley system
- Inflated

Introduction to Membrane Structures

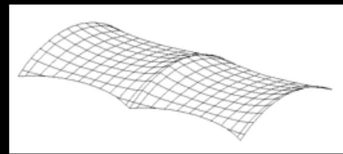
The Main Shapes & Forms Considered Here



Hypar



Conic



Barrel Vault

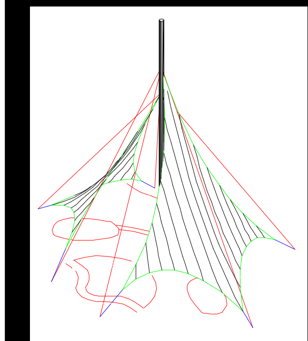
Introduction to Membrane Structures

Choice of surface form 1 : Hypar

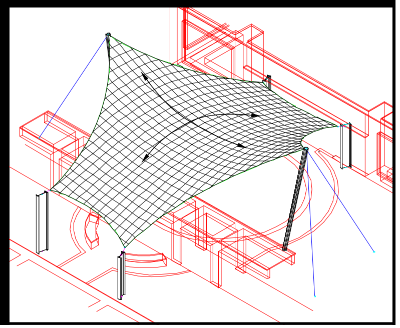
- Basic four point sail – two high points, two low points
- More than one sail, combined to produce more dramatic effect
- Not limited to four connection points - five, six or more connection points can be used

Introduction to Membrane Structures

Shape & Form



- Anticlastic (Doubly curved)
- Opposing curvature in orthogonal directions
- Minimal surfaces
- Basic form: Hyperbolic Paraboloid (Hypar)



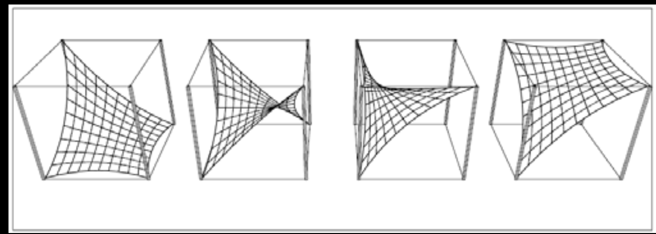
LSAA Introduction to Membrane Structures

Choice of surface form 1: Hypar

- Classic ‘Saddle’ shape
- In its most basic form, membrane tensioned between ‘saddle’ shaped supporting steelwork.



LSAA Introduction to Membrane Structures



A simple 4 sided hypar has the 4 corner points not in the one plane.
Quite different shapes can be generated – as in the basic cube boundaries.

Joining opposite sides is a series of straight lines.
Joining diagonally gives the two opposing curves or a “saddle shape”

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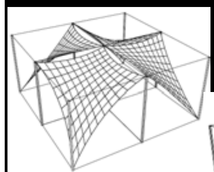
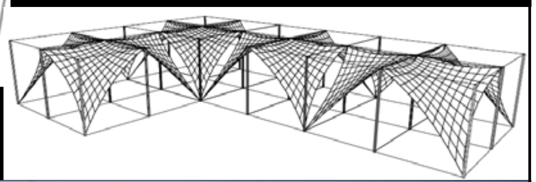
LSAA Introduction to Membrane Structures



Note: Included angles = 90+90+90+45
Sum = 315 deg. Difference = 360-315 =45 deg




Multiple hypars used at Yulara
Orientate to maximize shade
whilst maintaining air flows.

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Choice of surface form 2 : Barrel Vault

Membrane tensioned between two arches with scallop edges

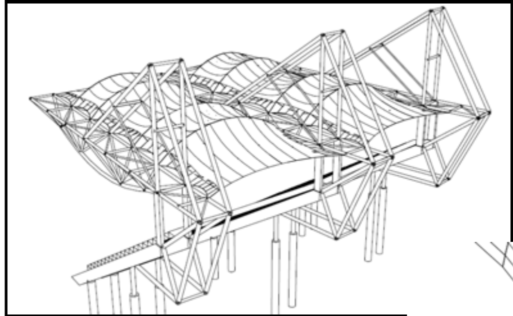
Urban Loritz Platz Vienna

BRDC Clubhouse UK

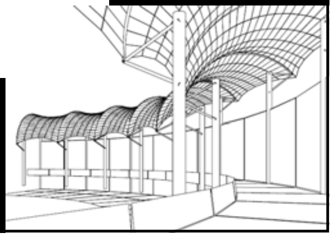
Hua Shao Yu Ticket Office China

Introduction to Membrane Structures

Choice of surface form 2 : Barrel Vault



Preliminary layout for the Gabba Grandstand roofs



Curved covered walkway

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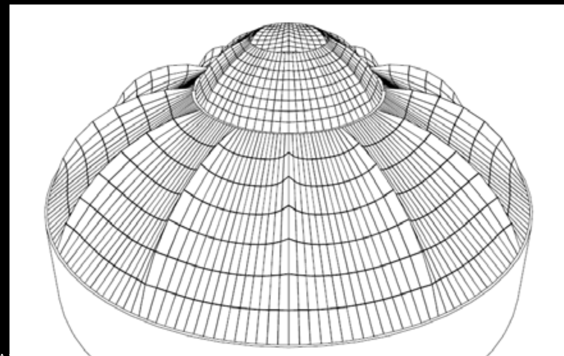
Choice of surface form 2 : Barrel Vaults used for a Dome



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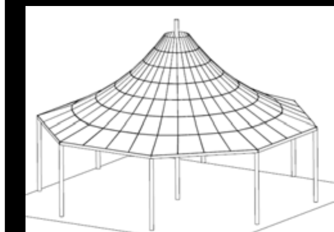
Introduction to Membrane Structures

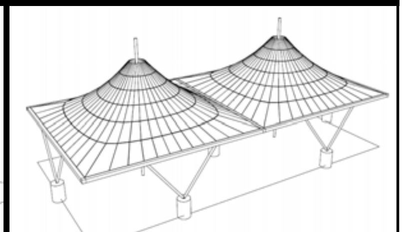
Choice of surface form 3 : Conical Membranes

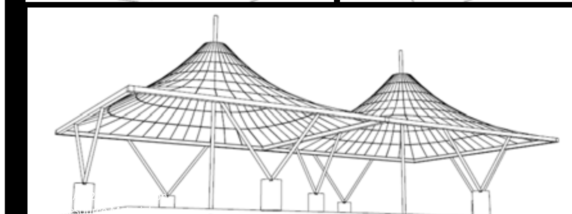
- Membrane tensioned between smaller upper ring and some form of lower boundary.
- Scallop (catenary) edges along over boundary
- Fixed edges along lower boundary

Introduction to Membrane Structures

Choice of surface form 3 : Conical Membranes







Octagonal & multiple four sided cones studies.

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Choice of surface form 3 : Conical Membranes

AfA Vehicle Park Germany

Glyndebourne UK

Butlins Pavilion UK

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Choice of surface form 3 : Inverted Conical Membranes

- Same design principles as normal cone structure.
- Limiting case is often a wind uplift load case

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Choice of surface form 4 : Ridge Valley System

Ashford Retail Park

- Double curvature formed by tensioning membrane between alternating 'hogging' and 'sagging' cables
- Cables alternate, above and beneath the fabric

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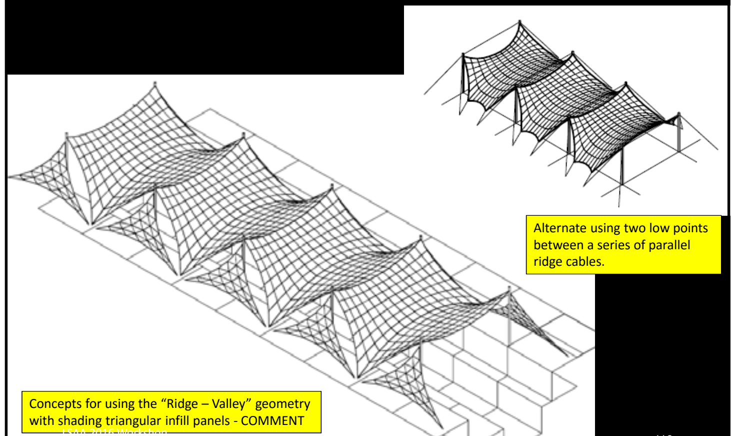
Choice of surface form 4 : Ridge Valley System



Alternate using two low points between a series of parallel ridge cables.

Concepts for using the "Ridge – Valley" geometry with shading triangular infill panels - COMMENT

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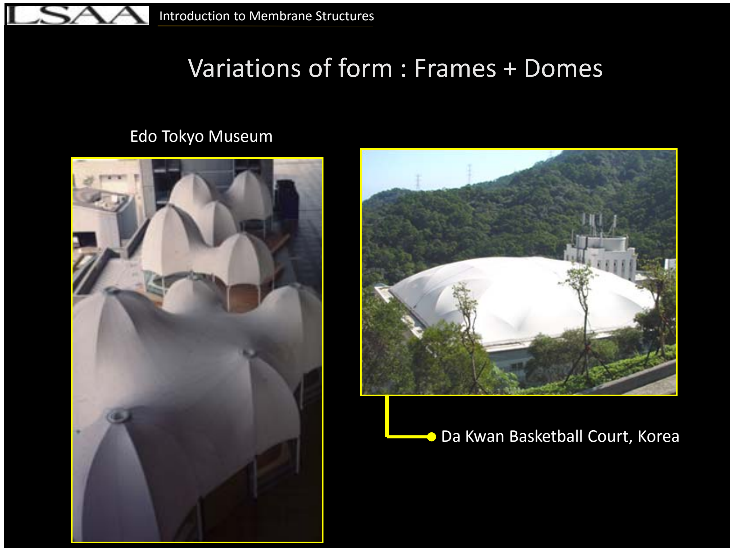
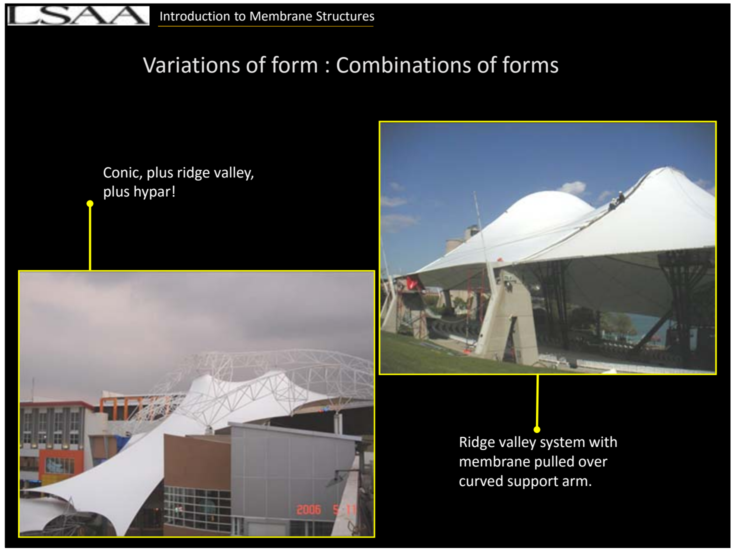
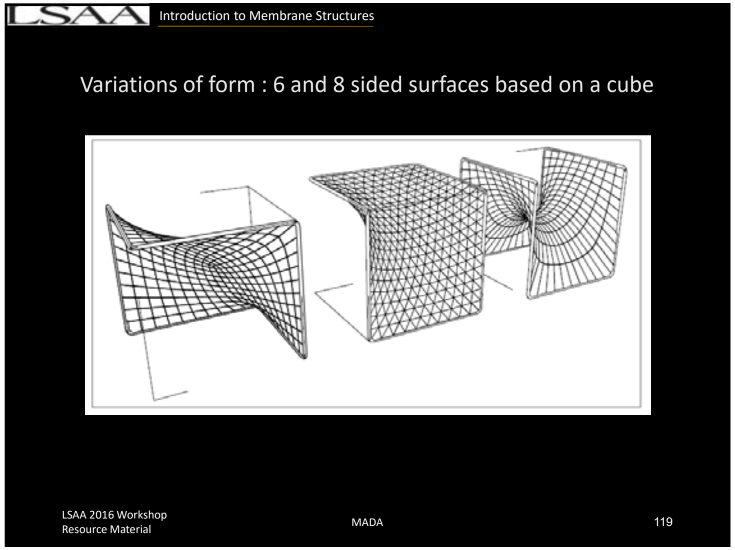

Introduction to Membrane Structures
Variations of form : Frames + Domes
Edo Tokyo Museum
Da Kwan Basketball Court, Korea


Introduction to Membrane Structures
Variations of form : Combinations of forms
Conic, plus ridge valley, plus hypar!
Ridge valley system with membrane pulled over curved support arm.


Introduction to Membrane Structures
Variations of form : 6 and 8 sided surfaces based on a cube
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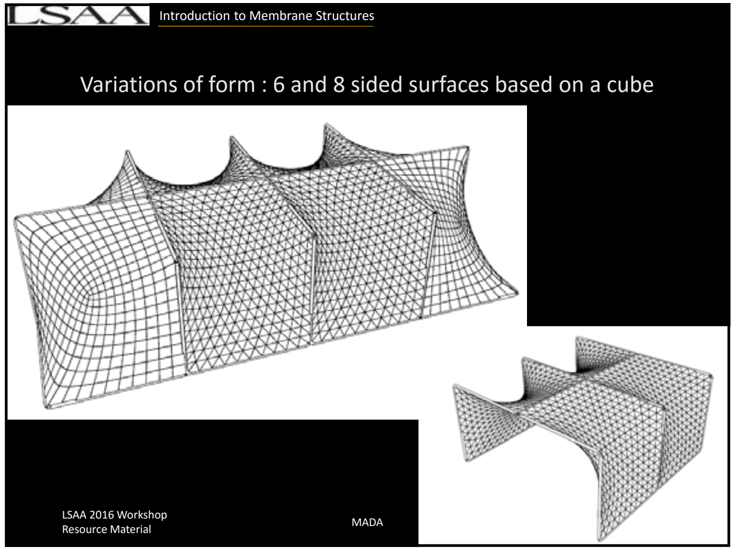
Introduction to Membrane Structures
Variations of form : 6 and 8 sided surfaces based on a cube
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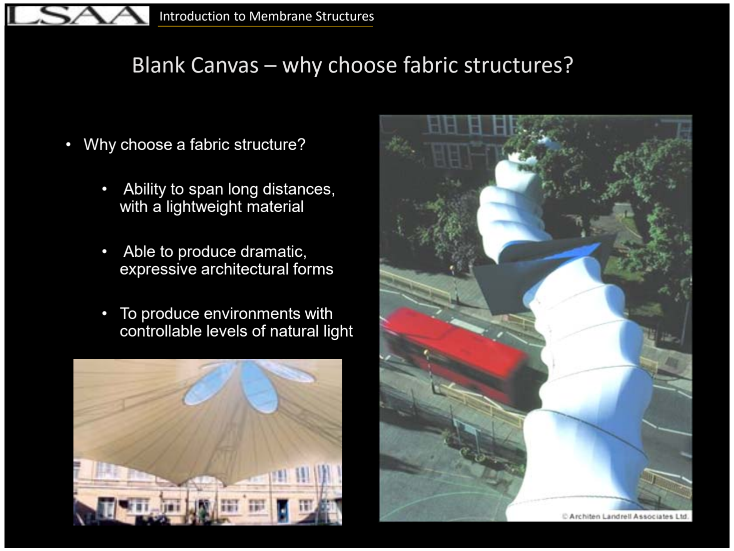
Inflated structures

- Inflatable structures :
  - Helium filled
  - Air inflated ‘cushions’
- Requires more specialist knowledge and techniques for design and engineering.
- Additional fabric property requirements – leakage properties

Surface Form Possibilities

“The only limitation is your imagination”

The Design Process for Tension Membrane Structures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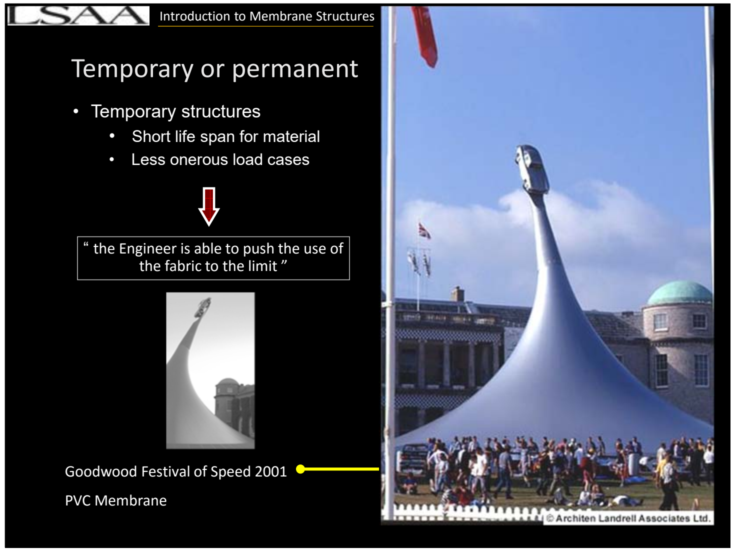
Introduction to Membrane Structures
Blank Canvas – why choose fabric structures?
• Why choose a fabric structure?
• Ability to span long distances, with a lightweight material
• Able to produce dramatic, expressive architectural forms
• To produce environments with controllable levels of natural light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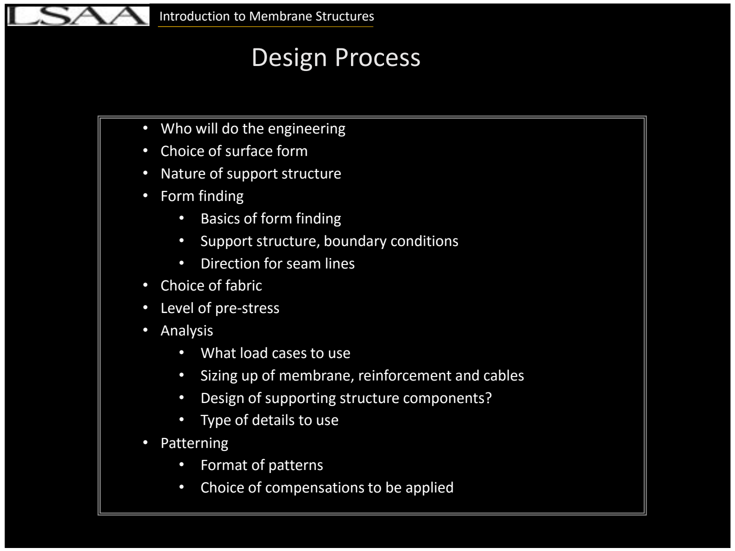
Introduction to Membrane Structures
Temporary or permanent
• Temporary structures
• Short life span for material
• Less onerous load cases
" the Engineer is able to push the use of the fabric to the limit "
Goodwood Festival of Speed 2001
PVC Membrane
© Architen Landrell Associates Ltd.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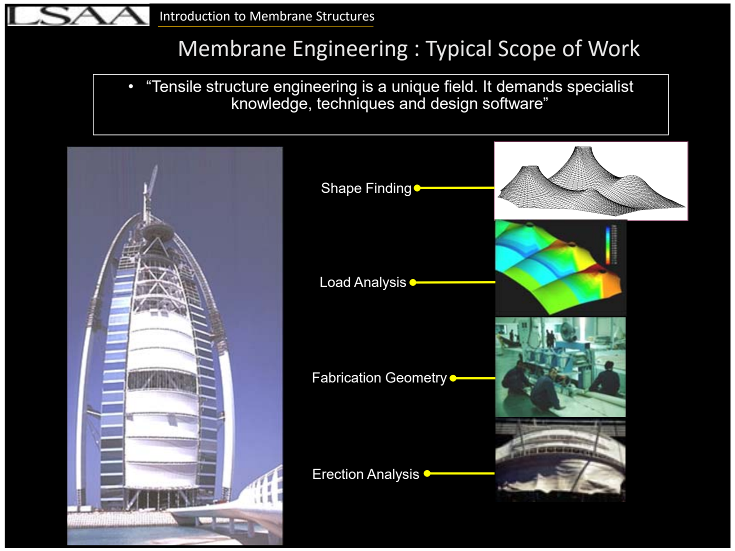
Introduction to Membrane Structures
Design Process
• Who will do the engineering
• Choice of surface form
• Nature of support structure
• Form finding
• Basics of form finding
• Support structure, boundary conditions
• Direction for seam lines
• Choice of fabric
• Level of pre-stress
• Analysis
• What load cases to use
• Sizing up of membrane, reinforcement and cables
• Design of supporting structure components?
• Type of details to use
• Patterning
• Format of patterns
• Choice of compensations to be applied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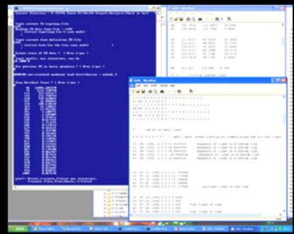
Introduction to Membrane Structures
Membrane Engineering : Typical Scope of Work
• "Tensile structure engineering is a unique field. It demands specialist knowledge, techniques and design software"
Shape Finding
Load Analysis
Fabrication Geometry
Erection Analysis

Introduction to Membrane Structures

Specialist engineering

- The specialist engineering methods and knowledge required for the design of a tensile structure (form finding, load analysis and fabrication data), can be sourced in one of two ways:
  - Use of external specialist consultants
  - In house, using commercially available tensile structure FE software.



BEWARE of ‘black box’ software.

Powerful potential, but requires thorough understanding.

– Who will undertake the engineering

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Introduction to Membrane Structures

Nature of supporting structure

- “For the most part, the nature of the supporting structure is governed by the choice of the surface form, however, there are still some issues to be explored”.

– Hypar, choice of edge supports
  - Solid 3 strut tripod arrangement
  - Bipod arrangement (2 struts,1 tie cable).
  - Single strut and two tie cables
  - Timber struts
  - Steel struts
  - Connection to existing building

– Barrel vault, membrane pulled over arch.
  - Steelwork arch
  - Timber arch

Introduction to Membrane Structures

Choice of supporting structure

– Conical membrane
  - Support for central head ring
    - Supported with column
    - Suspended
    - Flying struts

Introduction to Membrane Structures

Choice of supporting structure

- Lower edges
  – Scallop (catenary edges)
  – Continually fixed (arch)
  – Steelwork boom supports
  – Connected to existing building

– Nature of support structure

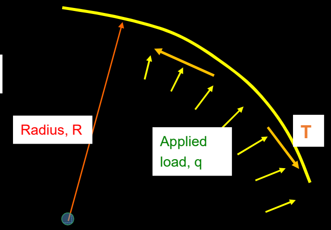
Membrane form finding

"THE SHAPE AND CURVATURE OF THE MEMBRANE DEFINES ENTIRELY HOW THE STRUCTURE WILL CARRY LOAD"

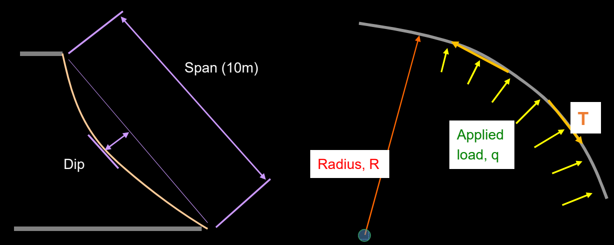
- Form finding is the first stage of any tensile structure analysis
- There is one basic equation which describes the behaviour of all tensile structures:

Membrane stress = Radius x Applied load

T = R . q

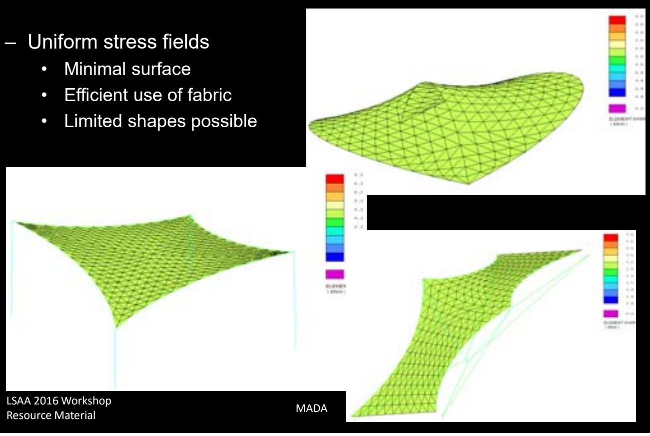


Membrane form finding



Membrane form finding – "Soap Films"

- Uniform stress fields
  - Minimal surface
  - Efficient use of fabric
  - Limited shapes possible

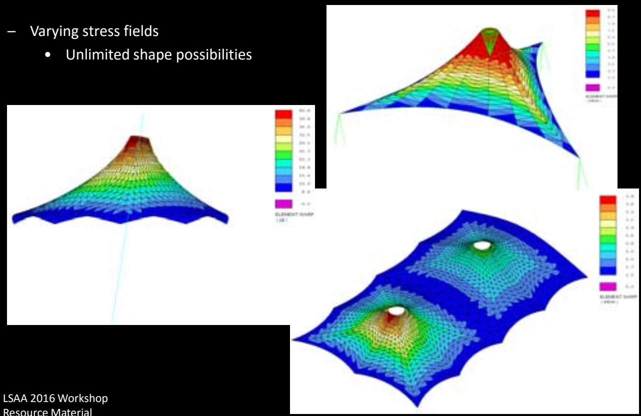


Soap Films

- Early physical means of form finding
- Not suitable for many structures such as higher cones
- Computer software can simulate soap films and non-uniform stress fields
- May not represent ideal shapes for environmental loads (wind, snow etc).
- Photos from IL early work.

Membrane form finding

- Varying stress fields
  - Unlimited shape possibilities

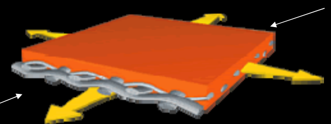


Traps for Architects

- Curved surfaces available in most CAD systems do not consider fabric stresses and are therefore very unlikely to be a valid shape.
- There is a tendency to design structures that do not have double curvature (saddle shape), or adequate curvature.
- There is a tendency to conceive of surfaces which are too flat and may lead to problems such as water ponding.
- The overall design time can be significant and with the cost of details will result is a very high cost for small structures. ($/sqm). Do not use the basic cost of the fabric as the basis for the project budget.
- You need to engage the specialists early in the design process. Erection procedures are critical for larger spans.

Choice of direction for seam lines – discuss with Eng. and Fabricator.

- 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



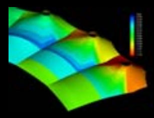
Typical Woven Structural Fabric Architecture

Choice of direction for seam lines - examples

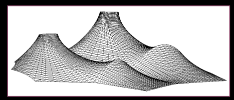
Introduction to Membrane Structures

Level of pre-stress

- 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

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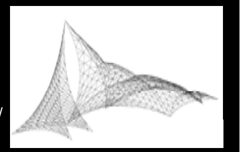
Introduction to Membrane Structures

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

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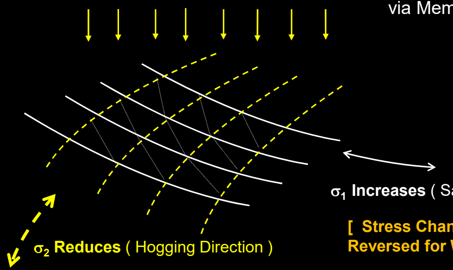
Introduction to Membrane Structures

Load Analysis

Fabric structures are wind sensitive – will need to consider multiple load cases & wind directions as well as "prestress".

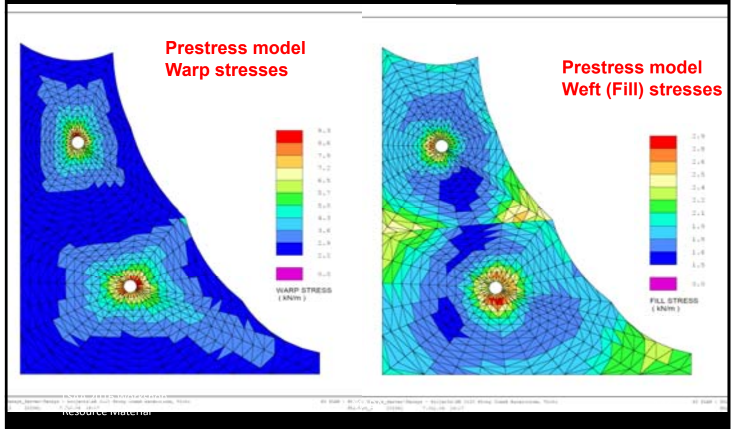
Wind and Snow Loading Applied to Current Deformed State via Membrane Element Surfaces



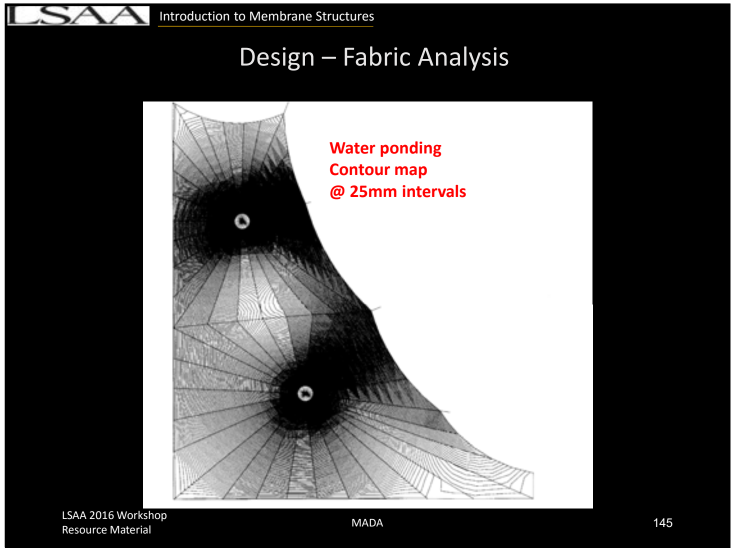
Material Elastic Properties and Selfweight Introduced into Prestress Equilibrium Form

Introduction to Membrane Structures

Design – Fabric Analysis



Resource Material


Introduction to Membrane Structures
Design – Fabric Analysis
Water ponding
Contour map
@ 25mm intervals
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Resource Material
MADA
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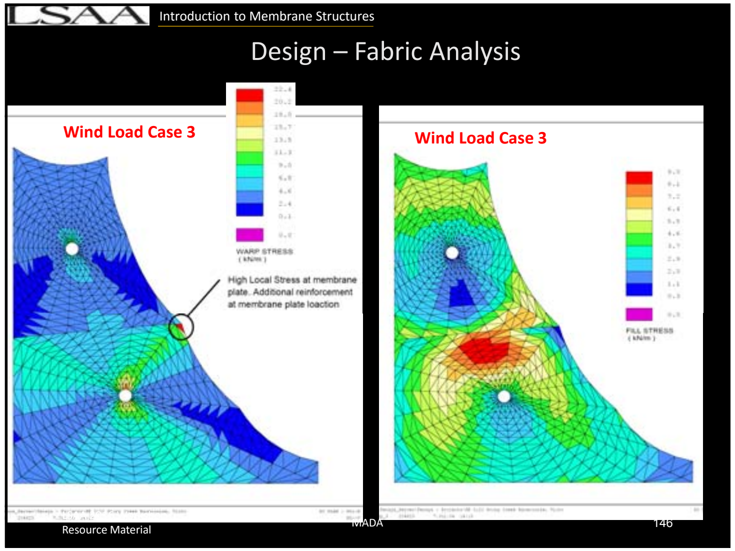
Introduction to Membrane Structures
Design – Fabric Analysis
Wind Load Case 3
WARP STRESS
High Local Stress at membrane plate. Additional reinforcement at membrane plate loaction
Wind Load Case 3
FILL STRESS
Resource Material
MADA
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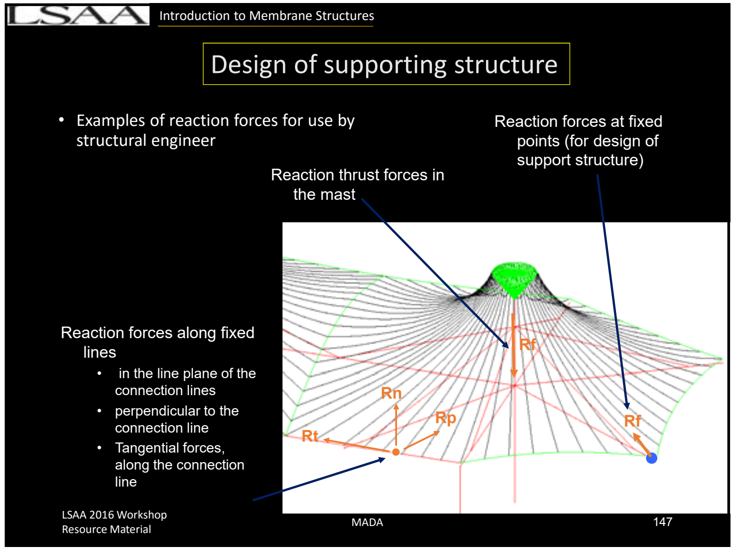
Introduction to Membrane Structures
Design of supporting structure
Examples of reaction forces for use by structural engineer
Reaction forces at fixed points (for design of support structure)
Reaction thrust forces in the mast
Reaction forces along fixed lines
in the line plane of the connection lines
perpendicular to the connection line
Tangential forces, along the connection line
Rf
Rn
Rp
Rt
Rf
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Resource Material
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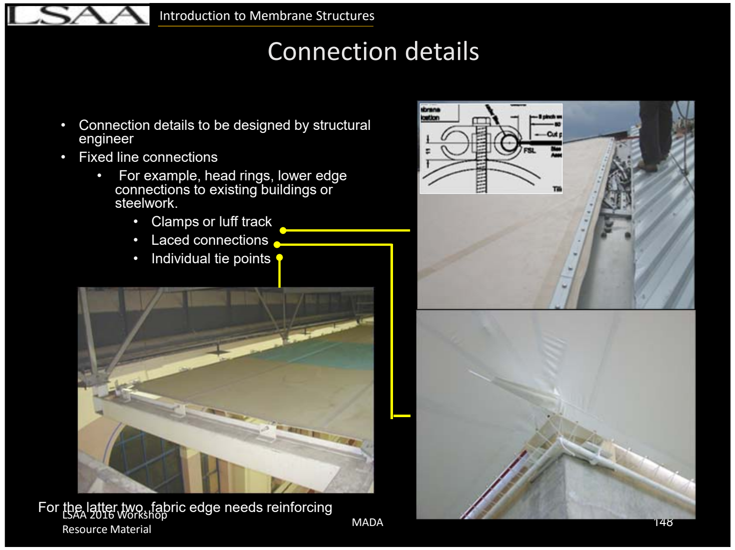
Introduction to Membrane Structures
Connection details
Connection details to be designed by structural engineer
Fixed line connections
For example, head rings, lower edge connections to existing buildings or steelwork.
Clamps or luff track
Laced connections
Individual tie points
For the latter two, fabric edge needs reinforcing
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Connection details

- Edge Scallops
  - Cables in pockets
  - Use of C-clips
  - C-clips also useful for site connection
  - C-clip detail will require cover flap

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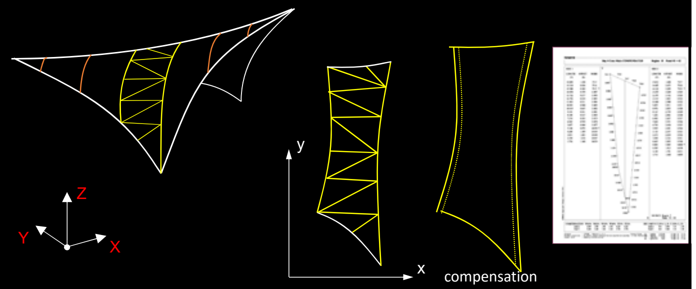
Pattern Unfolding



three dimensional surface strip unfolded into a 2D plane then compensated for prestress

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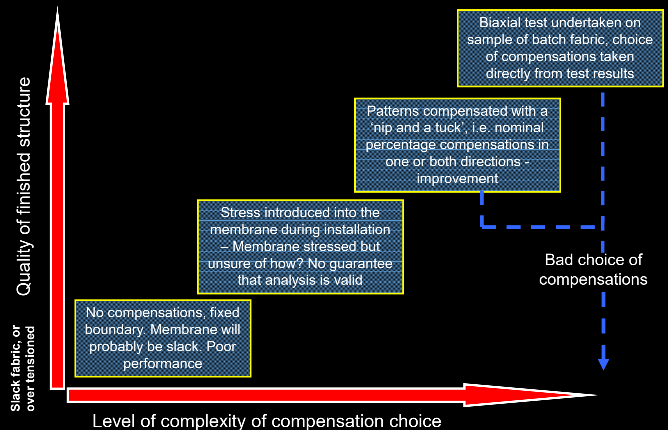
Pattern Compensation



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Fabrication, Construction and Installation Processes

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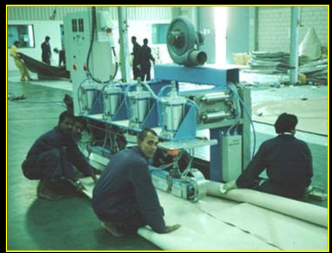
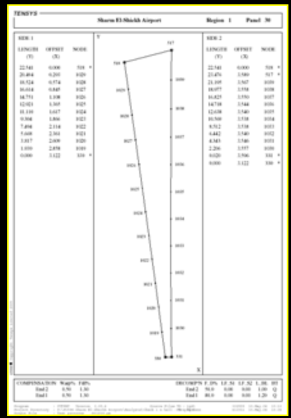
Fabrication – Cutting Pattern Output





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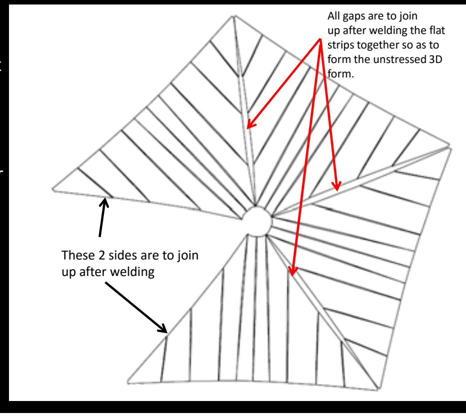
Each strip is carefully cut using a computer driven cutter / plotter.

The strips are welded (high frequency) together making sure to line up "match points" on each adjacent strip.

4 sided cone example.



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Titans Stadium Robina, Qld

Hightex Pty Ltd.

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Typical Fabrication Floor

Atkins Fabrications – Melbourne

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PTFE Glass panel bundled for shipping

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Robina Stadium – fabric handling.

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Robina Stadium – membrane transport

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Welding seams on flashing using hand tacker
Robina Stadium

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Robina Stadium – over flashing.

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Robina Stadium

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Novel temporary “access platform” Robina Stadium

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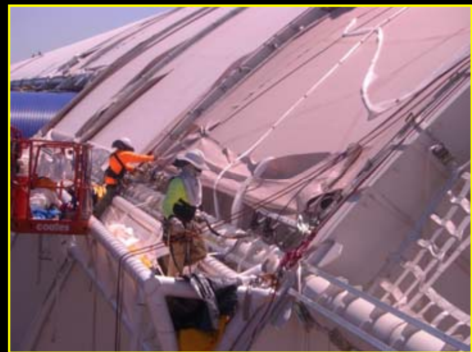
Specialised handling trough – Robina Stadium



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Rope access to Robina stadium flashing works.

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Robina Stadium – rope access.

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Robina Stadium – preparation.

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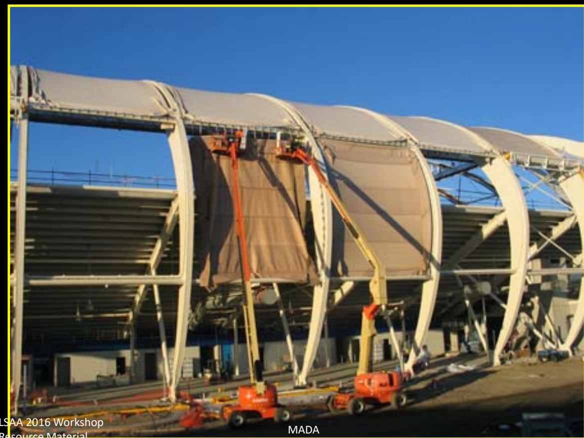
Robina Stadium – wall elements.



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Robina Stadium – corner.

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Robina Stadium – complete.

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RAS - Melbourne

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RAS – Melbourne - interior.

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RAS – Melbourne – ground activity.

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RAS – Melbourne – lifting pods aloft.

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RAS – Melbourne – Steelwork stood and guyed off.

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RAS – Melbourne – Membrane ready to lift by winch.

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RAS – Melbourne – lifting process under way.

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RAS – Melbourne – lift as seen from outside.

Oasis Tension Structures – Melbourne

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Stressing the masts at RAS - Melbourne

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RAS – Melbourne - interior.

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MSAC Swimming Pool _ Melbourne – crawl space scaffold access
Mak Max - Brisbane

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MSAC – pool roof - 40 metre spreader lifting single panel.

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MSAC – Melbourne – panel being spread.

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Introduction to Membrane Structures

Conclusions

- Brief history of membrane structures and LSAA
- Basic principles of tensioned membrane structures
- Introduction to modern textile materials
- Examination of the various supporting elements
- Closer examination of tensile cables
- Engineering Design Processes
- Practical aspects of project realization

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