Structural Branch

The Structural Branch of EA, Victoria Division
in conjunction with the
Lightweight Structures Association of Australasia
would like to invite you to a technical seminar

Engineering Principles of Tension Membrane Structures

Wednesday Afternoon October 29th 2008 at EA Auditorium, 21 Bedford St, North Melbourne

Tensioned membrane structures have become an important structural form for both large span roof structures as well as for smaller covered areas where elegant architectural solutions are required.

The design principles and material properties needed to be understood for a successful realization of a project are not often covered in University courses. This seminar is an opportunity to learn about the basic structural design parameters, material selection, fabrication and erection techniques**.**

Topics which will be presented

- Brief history of tensile structures
- Understanding fabric materials
- Understanding the supporting structures
- Understanding the engineering design process
- Fabrication, construction and installation processes
- The future directions for lightweight structures

Speakers:

Dr Kourosh Kayvani – President LSAA and Principal, Structural Group (NSW) of Connell Wagner who has been responsible for the design of the new Wembley Stadium roof in the UK amongst other major projects.
Ian Knox – Managing Director of Innova International and LSAA member representing the architectural textiles industry, identifying and reviewing major technical fabric groups.
Rowan Murray – General Manager Ronstan Architectural and LSAA Secretary with specialist knowledge of cables and fittings needed in most structures.
Peter Lim – Managing Director, Tensys Engineers - Specialist Consultants for Lightweight Structures. Peter has been recognized for his fine work with numerous International Design Awards.
David McCready – Life Member of LSAA with decades of design, fabrication and installation experience of tension membrane structures.
Dr Peter Kneen – Executive Officer LSAA who is a pioneer structural engineer in Australia in many areas of lightweight structures

Sponsors – Tension Structures Fabric Suppliers

MEHLER TEXNOLOGIES	FERRARI	HIRAOKA	HVG HALIFAX VOGEL GROUP

Program

14.45	Registration & Networking with Sponsors
15.15	Welcome and Introduction - Chairman IEAust Structural Branch Introduction & Brief History of Tensile Structures - LSAA President
15.40	Materials – Textile Options for Diverse Architectural Applications - Ian Knox
16.00	Materials - Understanding Support Structures - Rowan Murray & Peter Kneen
16.30	Afternoon Tea break
17.00	Design Processes in Tension Structure Projects - Peter Lim
17.40	Fabrication, Construction and Installation Processes - David McCready
18.20	Future Directions – Peter Kneen
18.40	Closure

Date: Wednesday 29th October, 2008
RSVP: **Friday 24th October, 2008**
Time: **2.45pm Registrations, for Seminar, 3.15 to 6.45pm**
Venue: **EA Auditorium, 21 Bedford St. Nth Melbourne**
Cost: **$55** (Attendees will have access to papers and presentations and attendance will count towards CPD requirements)

SEMINAR REGISTRATION FORM: Wednesday, 29th October, 2008

RSVP Friday, 24th October, 2008

Title: First name: **Surname**:

Position: ______________________________ Organization: ______________________________

Address: ____ Postcode

Work Telephone: ______________ Mobile: ____________________ Email: ______________________________

☐ Please find my cheque enclosed for $.................... OR

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To confirm your booking return this form to:
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(ABN 18 572 571 513)
Engineering House
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Web: www.vic.engineersaustralia.org.au

EA - LSAA 2008 Technical Seminar

Introduction & Brief History of Tensile Structures

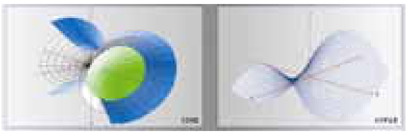
Dr Kourosh Kayvani
President LSAA

Introduction

- Welcome to our Technical Seminar
- The aim of LSAA is to promote proper application of lightweight structures including:
  - Tension membrane structures
  - Cable structures
  - Shell and folded structures
  - Space grids

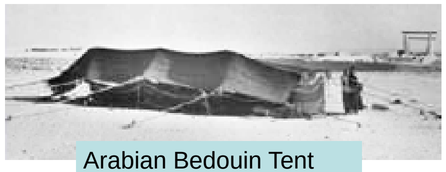
What is a Tension Membrane Structure?

- 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)



One of the earliest form of constructed shelter

North American Tipi



Arabian Bedouin Tent

Mongolian Yurt

Development of Tensile Surface Forms

- Use of double curvature by Vladimir Shukhov (Russian exhibition 1896)

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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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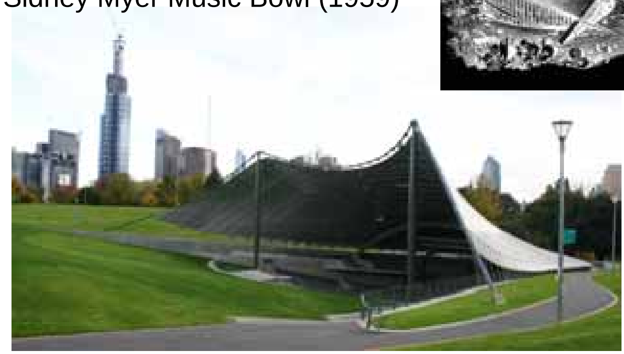
Cable Net Tensile Forms

- Raleigh Arena, USA (1953)
- Sidney Myer Music Bowl (1959)



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Application of Cable Nets

- German Pavilion, Expo Montreal (Otto, 1967)

- Larger spans achieved!

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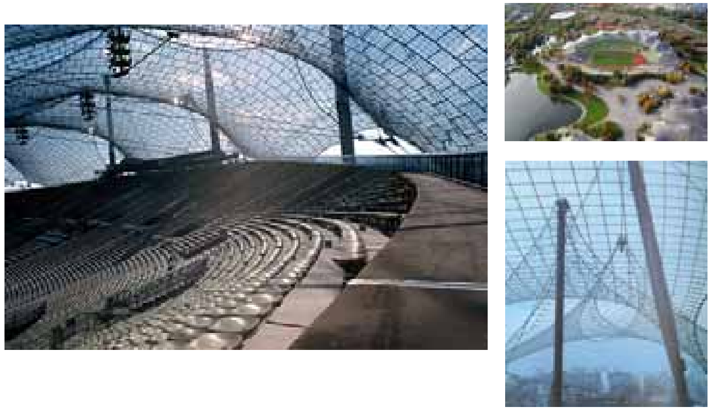
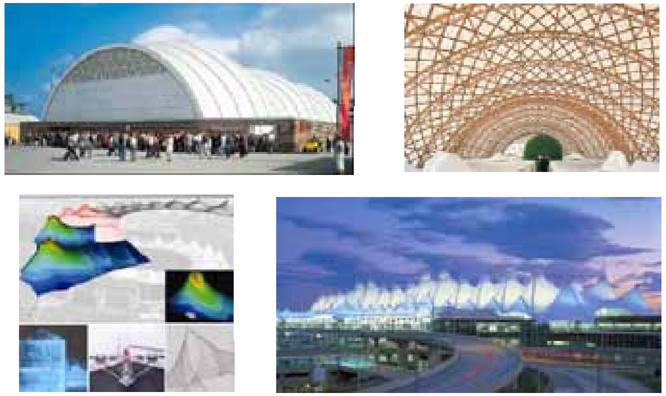
Munich Olympic Stadium (1972)



Emergence of Long-span Fabric Enclosures



Zaragoza Bullring, Spain (SBP, 1990)

Frankfurt Football Stadium (SBP, 2006)

Technical Program

- Materials - Textile Options -*by Ian Knox*
- Materials - Support Structures -*by Rowan Murray & Dr Peter Kneen*
- Design Processes -*by Peter Lim*
- Fabrication and Installation -*by David McCready*
- Future Directions -*by Dr Peter Kneen*

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TEXTILES FOR ARCHITECTURAL STRUCTURES

IAN KNOX – INNOVA INTERNATIONAL

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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.

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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

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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.

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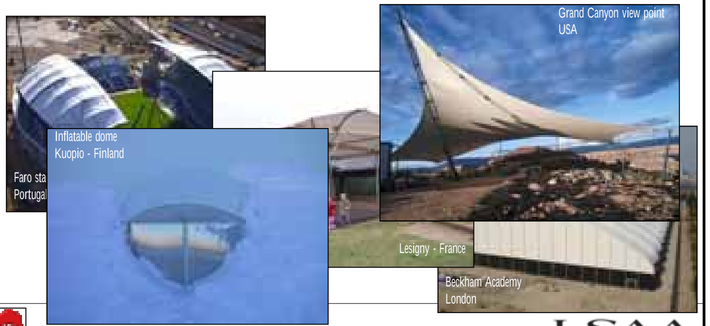
TEXTILES FOR ARCHITECTURAL STRUCTURES IAN KNOX – INNOVA INTERNATIONAL

Limitless Applications

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



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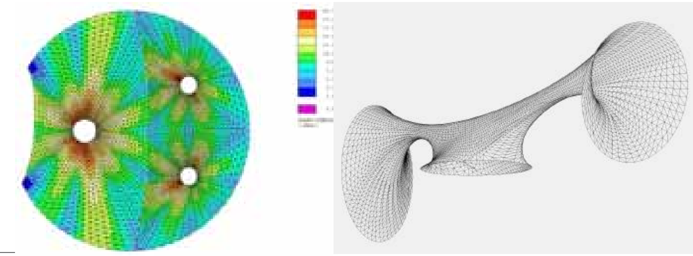
Engineering

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.



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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

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Types of Fabrics

Today we focus on five preponderant types of architectural textiles:

- P.T.F.E. Polyethylene Tetrafluoride on Fibreglass base fabrics
- P.V.C. / P.V.D.F. / P.E.S. Polyvinylchloride with Polyvinylidene Fluoride on Polyester base fabrics
- E.T.F.E. Ethylene-tetrafluroethylene
- H.D.P.E. Shadecloth High Density Polyethylene
- Silicone Coated Fibreglass

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1. PTFE

Millennium Dome
(O 2 Stadium) London

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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	Thickness	Tensile Strength	Elongation	Light Transmittance
1380 gsm	800um	450daN/3cm	10 %	11 %

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2. PVC / PVDF / PES

Hotel Foyer
Cairns

F1 Kuala Lumpur - Malaysia

Lake Pontoon
New York state

Rio de Janeiro - Brazil

Australian Textile projects win worldwide recognition

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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

	Weight	Tensile Strength	Tear Strength	Coating
Type 1				
Type 2				
Type 3				
Type 4				
Type 5	1500 gsm	1000/800 daN/5cm	160/140 daN	PVC PVDF

1000daN/5cm equates to 20 tonnes of tension per metre at the point of destruction

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

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3. ETFE

- 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 %	

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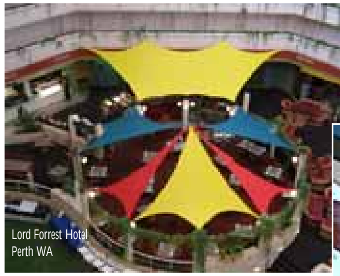

4. HDPE Shadecloth

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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	

HDPE 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.
- Finds service in a wide variety of shading applications.
- Flexibility through wide width and broad colour range.
- Lowest cost with lower engineering input requirements.

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 %

TEXTILES FOR ARCHITECTURAL STRUCTURES IAN KNOX – INNOVA INTERNATIONAL

In Conclusion

- 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.
- Other speakers will further demonstrate the genuine value such structures are now delivering world-wide.

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TEXTILES FOR ARCHITECTURAL STRUCTURES IAN KNOX – INNOVA INTERNATIONAL

My thanks and acknowledgement go to the following organisations for their assistance.

- Makmax Australia — Brisbane
- Tensys Engineers — Melbourne
- Rainbow Shade Products — Brisbane
- Port Douglas Sailmakers — Cairns
- Shade to Order — Newcastle
- Ferrari S.A. — France

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EA - LSAA 2008 Technical Seminar

Engineering Principles of Tension Membrane Structures

Melbourne, EA Auditorium, October 29 2008

EA - LSAA 2008 Technical Seminar

Materials – Understanding Support Structures

Rowan Murray & Peter Kneen

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

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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

EA LSAA Engineering Principles of Tension Membrane Structures

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Saddle shaped surfaces

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

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Typical Cone Structure

EA LSAA Engineering Principles of Tension Membrane Structures

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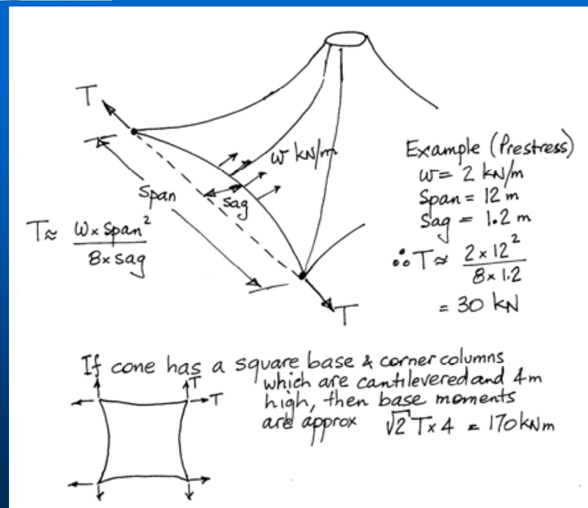
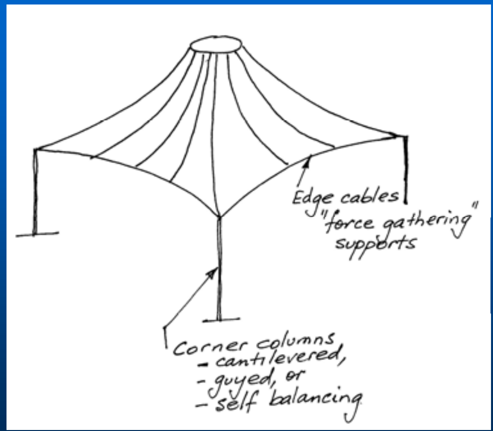


Engineering Principles of Tension Membrane Structures

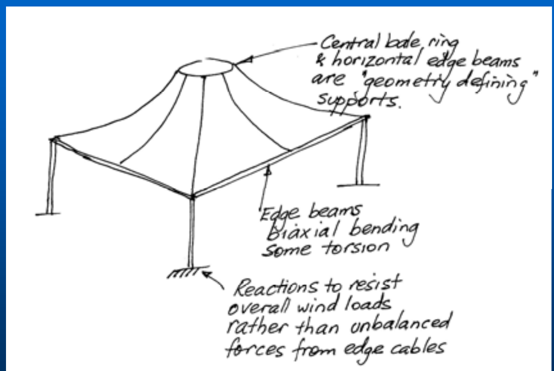


Engineering Principles of Tension Membrane Structures

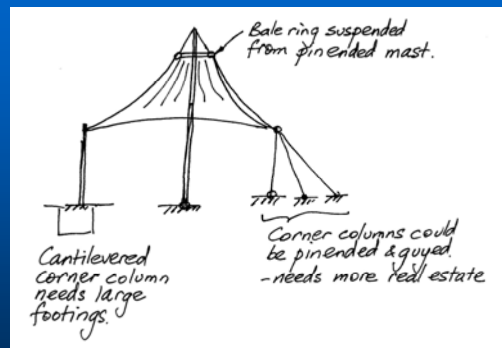
Typical small bale ring – 4 segments, 4 lifting points

Fabric stresses will cause bending and torsion in the bale ring

Engineering Principles of Tension Membrane Structures

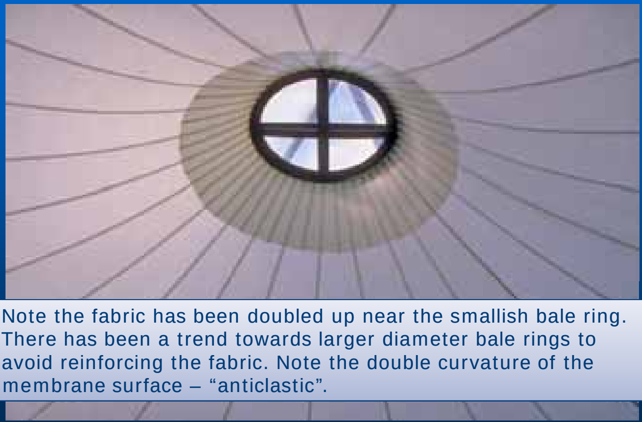


Engineering Principles of Tension Membrane Structures



Engineering Principles of Tension Membrane Structures

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 WC?

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.

This is an early example of an inverted cone supported on a cantilevered tubular column and outriggers.

The membrane was prestressed by tightening threaded rods to the bale ring at the bottom.

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

External pin ended masts and edge cables.

Cables as force gatherers.

Cables arranged as a petal to gather fabric stresses at several overhead pick up points.

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

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.

A set of masts (16 – 26m long) assembled for lifting.

These masts are nearly 100m tall to support the cable net and fabric dome (1km in circumference)

A classic undulating 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.

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

An approximate analysis might assume that the vast majority of downward wind loads are resisted by the high points and any uplift is taken by the low points.

Arches form a common load carrying and geometry defining support.

Engineering Principles of Tension Membrane Structures

The fabric pick up points pivot from the top of the arch to permit more movements & imparting smaller lateral loads on the arch.

Engineering Principles of Tension Membrane Structures

Another perimeter arch form of support.

Engineering Principles of Tension Membrane Structures

Laminated timber arches offer a pleasing effect

Engineering Principles of Tension Membrane Structures

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Another 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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Different spans for edge cables, together with a ridge or valley cable may lead to an interesting geometry for the anchor plates to resolve the different forces present.

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Aerial gymnastics to achieve a functional internal shape.

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A series of radial ridge and valley cables 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.

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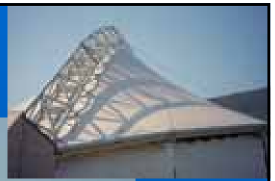

Engineering Principles of Tension Membrane Structures

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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.

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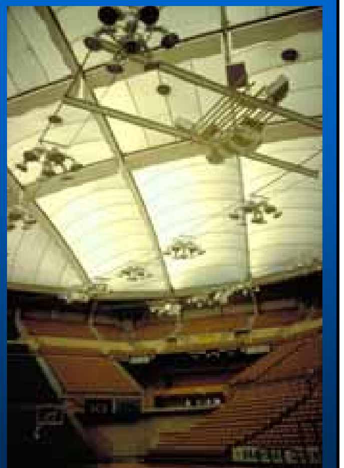
Looking up at the panels of an air-supported, cable restrained membrane structure.

The synclastic shape of the panels can be clearly made out.

Hanging curtains are to improve the acoustics.



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Two cone structures

Engineering Principles of Tension Membrane Structures


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Base of pin-jointed mast may be designed to be jacked so as to prestress the entire membrane surface.
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Splices can be designed to remain within the external diameter of the section
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Engineering Principles of Tension Membrane Structures


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“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.
Engineering Principles of Tension Membrane Structures

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Materials – Understanding Support Structures

"Load Transmitting" – Cables

Rowan Murray & Peter Kneen

1. Available Options for Tensile Members

a) Stainless Steel Cables

Grade 316 Stainless steel
1mm to 36mm Diameter
25N to 945kN BL

b) Galfan or Galvanized Steel Cables

High Strength Mild steel
Either Open Spiral Stand
Or Full Locked
8mm to 140mm Diameter
9kN to 20,000kN BL

Galfan is a coating system made up of 95% zinc and 5% aluminium

1. Available Options for Tensile Members

c) Synthetic & Composite Fibre Cables

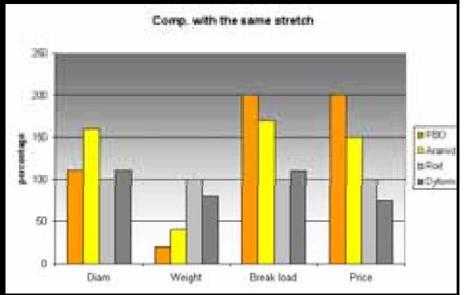
Super fibres - PBO (polybenzoxazole)
Aramid (Kevlar®)
Parafill

1. Available Options for Tensile Members

c) Synthetic & Composite Fibre Cables

Positives
- Superior mechanical Performance
- High Strength
- Low Weight
- Non conductive

Negatives
- High cost
- Poor lifespan due to low UV stability
- Low fire retardency
- Difficult to terminate



(Smart Rigging Oct 2008)
20mm PBO, 20mm Aramid,
40mm Rod, 14mm Dyform

1. Available Options for Tensile Members

c) Synthetic & Composite Fibre Cables

Australian Bicentennial Project – 1988
22 Structures of 10,000sqm

1. Available Options for Tensile Members

d) Webbing

Commonly used in shade structures utilizing knitted shade cloth
Webbing sewn into the cloth transfers the fabric stresses to the cable/webbing

Available Options for Tensile Members

e) Stainless Steel Rods

Grade 550 Stainless steel
Grade 460 Stainless steel
Grade 316 Stainless steel
5mm to 100mm Diameter
9kN to 3172kN BL

f) Mild Steel Rods

Grade 460 Carbon steel
Grade 520 Carbon steel
10mm to 100mm Diameter
33kN to 4551kN BL

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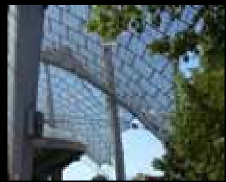

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Considerations for Selection of a Tensile Member

Consideration should be given to:

1. Load Capacity
2. Tendon Type – Cable or Rod
3. Material – Carbon or Stainless Steel (+ Composite Fibre)
4. Corrosion Protection – Galvanized, Galfan, Stainless, Plastic sheath (cables)

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Considerations for Selection of a Tensile Member

1. Load Capacity

GALFAN Coated Steel - Open Spiral Strands

NOMINAL CABLE DIAMETER mm	CABLE CONSTRUCTION	METALLIC CROSS SECTION AREA mm²	MINIMUM BREAKING LOAD kN	kg	lb	WEIGHT APPROX kg/m
8.1	1 x 19	[illegible]	[illegible]	[illegible]	[illegible]	0.3
10.1	1 x 19	[illegible]	[illegible]	[illegible]	[illegible]	0.5
12.2	1 x 19	87.0	134	[illegible]	[illegible]	0.7
14.1	1 x 37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1 x 37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	1 x 37	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
24.4	1 x 37	347.0	537	54790	120900	2.7
28.3	1 x 37	467.0	722	73670	162220	3.7
31.3	1 x 61	572.0	884	90204	198820	4.5
36.3	1 x 61	769.0	1189	121320	267180	6.1

This is a copy of the table for Galfan Open Spiral Strand
Selection charts are available for all cable and rod options.

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Considerations for Selection of a Tensile Member

2. Tendon Type – Cable Vs Rod/Bar

- Load characteristics
- Mechanical performance
- Corrosion Protection
- Aesthetics
- Logistical & transport considerations
- Cost
- Availability

Considerations for Selection of a Tensile Member

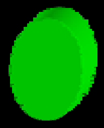
2. Tendon Type – Cable Vs Rod/Bar (cont.)

Load Characteristics

- *Cables are fabricated from high tensile wires allowing up to 3 times higher load than rod for the same cross section:*

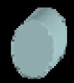
Tension bar S355 = 662kN
(460 bar 660kN = Ø 48mm)

Ø 56mm



Cable tension member VVS = 676kN

Ø 32mm



Considerations for Selection of a Tensile Member

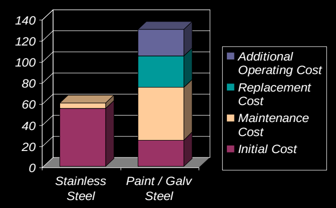
2. Tendon Type – Cable Vs Rod/Bar (cont.)

Criteria	Bar (Carbon steel 460)	Cable
Section	Single	Combination of wire sections
Fill factor f	1,0	0,74…0,89
Metallic cross section [mm²]	D²*π/4	(D²*π/4)*f
Modulus of Elasticity [KN/mm²]	210	150…160, ±10
Pre-stressing needed	No	Yes
Maximum production length [m]	Limited to 11m	Theoretical unlimited
Installation	Difficult bending	Relatively easy
Corrosion Protection	Galvanized	Galfan coating
Lifespan of corrosion protection [Years]	Ca. 10	Ca. 30
Bending (Pylon saddle)	No	Yes
Transport	Stiff bar: difficult	Coils: relatively easy
Creeping	No	Elongation ~0/.35 ‰
Tensile strength [N/mm²]	610	1450…1770

Considerations for Selection of a Tensile Member

3. Material - Carbon Steel Vs Stainless

- *Tensile/Mechanical Properties*
- *Aesthetics Requirements*
- *Performance/longevity (resistance to corrosion)*
- *Cost*



Source – Australian Stainless Steel Development Assoc Inc.

Considerations for Selection of a Tensile Member

4. Corrosion Protection

Use of the stainless steel material still offers the best resistance to corrosion in the majority of environments but not all. (e.g. chlorine environments are prone to cause SCC in stainless).

The options for the corrosion protection of carbon steel cables and rods are basically the same as for other mild steel products:

Passive corrosion protection (e.g. paint systems):
- The protection material insulates the aggressive elements from the steel.
- The disadvantage - if the protection layer gets damaged, the material below will corrode.
- Improved corrosion resistance is only possible by thicker or more resistant layers.

Active corrosion protection (e.g. zinc/galvanized systems):
- The protection material is reacts with oxygen and water to protect the steel.
- If scratched the protection material acts over a certain distance (self-healing process).
- Disadvantage of active corrosion protection systems - they get washed away over the time.
- Improvement is possible by increasing the thickness of the layer (3 X thicker lasts 3 X longer)

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Considerations for Selection of a Tensile Member

4. Corrosion Protection (cont.)

Main Options for Corrosion Protection

1. Stainless Steel
2. Galfan Coating
3. Galvanized/Zinc Coating
4. Plastic Sheathing

Galfan

- Combines both active and passive protection elements.
- A galvanized style of coating with 95% zinc and 5% Aluminium added.
- Minimum 4 times higher lifespan of heavy galvanizing.
- Superior self healing behavior to Zinc.
- Smooth surface
- Visual Appearance – Silver Grey
- Surface can be painted as with classic systems if required for coloring.
- Application is similar to hot dip galvanizing.
- Layer thickness: 300 gr/m2 average but not critical like galvanizing.

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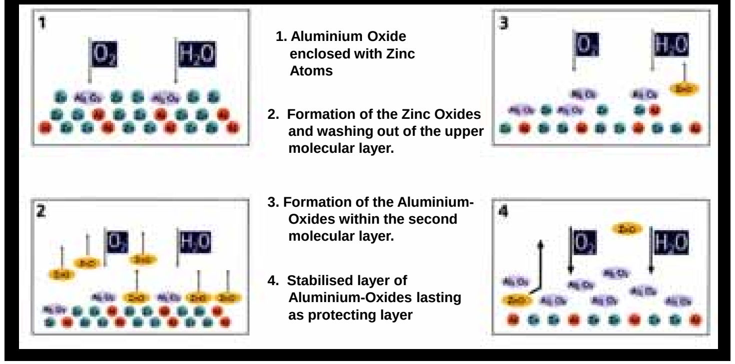
Considerations for Selection of a Tensile Member

4. Corrosion Protection (cont.)

The Galfan Protection System



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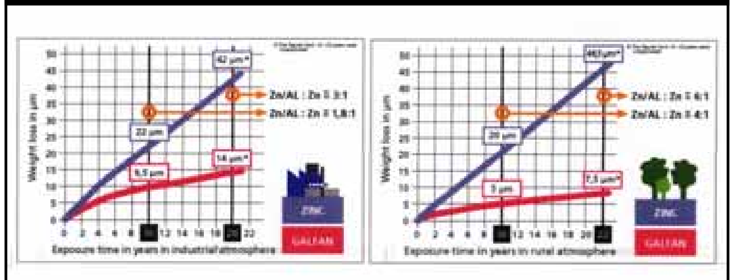
Considerations for Selection of a Tensile Member

4. Corrosion Protection (cont.)

Performance of the Galfan Coating



Source – Pfeifer Seil- und Hebetechnik GmbH Memmingen

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Nuage léger at the Grande Arche, Paris, France 1989

Galfan Cables – Socket Terminations

Center Court Rothenbaum, Hamburg, Germany 1998

Galfan Cables – Socket Terminations

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

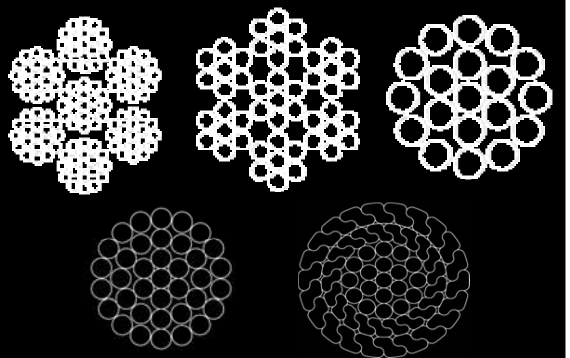
7 X 19
wire rope

7 X 7
wire rope

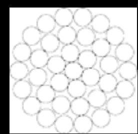
1 X 19
strand

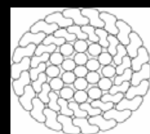
1 X 31
strand

VVS-3
Full locked cable



1. Cable Construction – Strand / Full Locked





Open Spiral Strand (OSS)

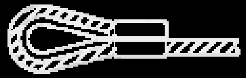
- Wire-Ø up to 5 mm
- Construction 1x19, 1x37, 1x61, 1x91
- E-Modulus 150 (130) ±10 kN/mm2
- Diameter 3 to 36 mm
- No closed section of the cable
- Galvanized wires/GALFAN+stainless
- Socketing and swaging possible
- Back stays
- Main and Tension cables
- Hanger Cables
- Support cables
- Handrail cables

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

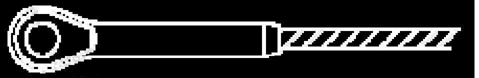
2. Cable Termination Methods

Swaged Ferrule eye



Wire rope grips

Swaged terminal end



Socket End.

2. Cable Termination Methods (cont.)

Swaged End Terminations – section through swage

2. Cable Termination Methods (cont.)

Socket End Terminations – Socketing process (cables above 36mm)

Stage 1

Stage 2

Stage 3

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?

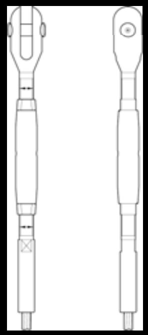
3. End Fitting Options

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

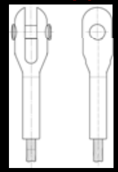
- Must transfer the load from and to the cable.
- Must not add to fatigue.
- Must match the corrosion protection system of the mating/surrounding structure.

3. End Fitting Options

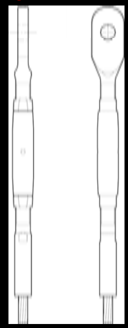
Swaged end terminations (up to 36mm)



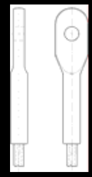
Open swaged fitting with turnbuckle



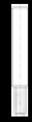
Open swaged fitting



Closed swaged fitting with turnbuckle



Closed swaged fitting



End stop

Threaded Terminal

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*

Applications;

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

Cable Diameters:
4mm through to 22mm

3. End Fitting Options

Swaged end terminations - Turnbuckles (Full Adjustment)

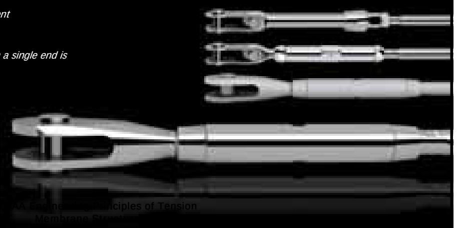
Features;

- *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*

Applications;

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

Cable Diameters:
3mm through to 36.5mm



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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*

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Hutt School, ***Wellington NZ*** **ACS2**

Stainless Cables – Swaged End Terminations

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Stainless Cables – Swaged End Terminations

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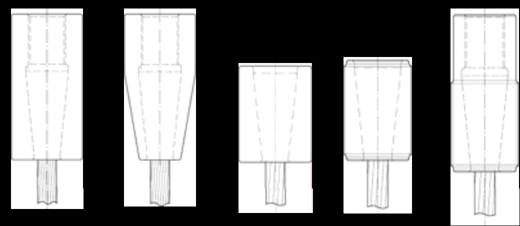
3. End Fitting Options

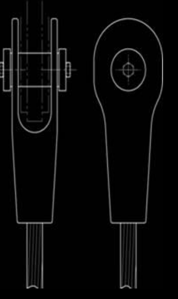
Socket End Fittings – 36mm and over.



Cylindrical socket with internal thread | Conical socket with internal thread | Cylindrical socket | Cylindrical socket with external thread | Cylindrical socket with internal and external thread

3. End Fitting Options

Socket End Fittings – 36mm and over.



Open spelter socket

3. End Fitting Options

Socket End Fittings – 36mm and over.

Features;

- *Utilizes Ronstan full locked cables*
- *Diameters from 21mm and up to 140mm*
- *Highest load capacity of all Ronstan cable systems (20,000KN BL)*
- *Socketed fittings*
- *Pre stretched and manufactured to design load (no tensioning)*

Applications;

- *Engineered structural applications where minimum elongation and cable behavior are paramount*
- *Bridge stays, Structural Bracing and Droppers*

Cable Diameters:

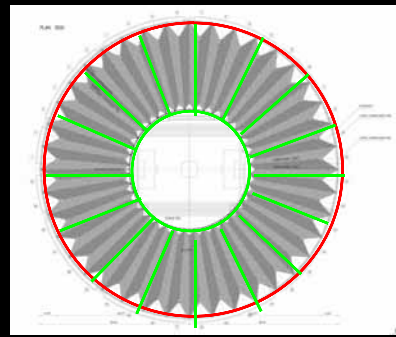
21mm through to 140mm Std
Have produced up to 250mm

Gottlieb Daimler Stadium, ***Stuggart*** A 70m clear span fabric roof with a minimal weight of 36kg/m² **ACS4**

Galfan Cable - Socket Fittings

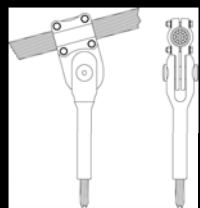
AOL Arena, ***Hamburg*** the same detail as Stuttgart but a smaller clear span

The Spoke Wheel



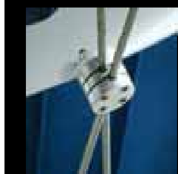
4. Connections, Clamps & Anchors

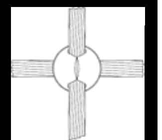
Cable Clamps

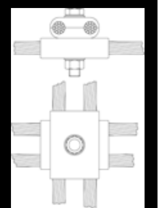


4. Connections, Clamps & Anchors

Cross Clamps

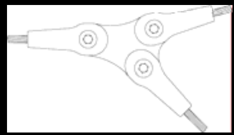


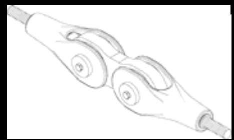




4. Connections, Clamps & Anchors

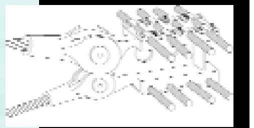
Cable to Cable Connectors





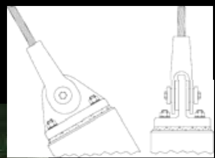
4. Connections, Clamps & Anchors

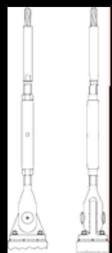
Cable Nodes



4. Connections, Clamps & Anchors

Anchors





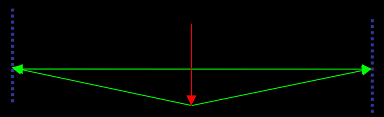
4. Connections, Clamps & Anchors

Membrane Plates

Cable Design Basics

Tension Only

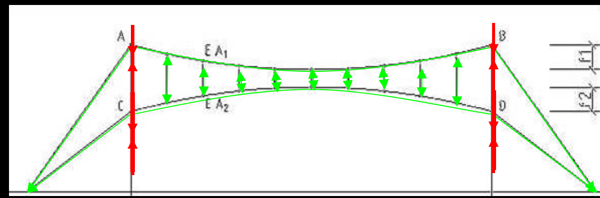
- Cables only work in tension.
- Perpendicular loads can only be taken with large deformation.



Cable Design Basics

Tension Only

- 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

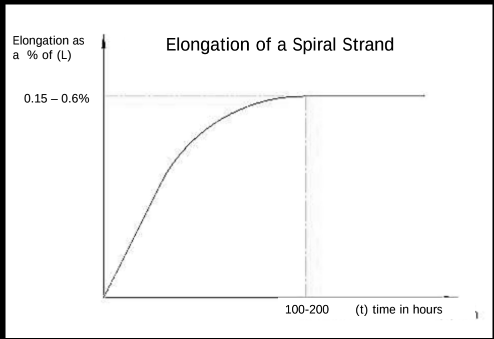
Cable Length

Main Influences on Cable Length

1. Cable Creeping
2. Setting of the cones (full locked cables only)
3. Elongation due to clamping
4. Temperature
5. Elastic elongation

Cable Length

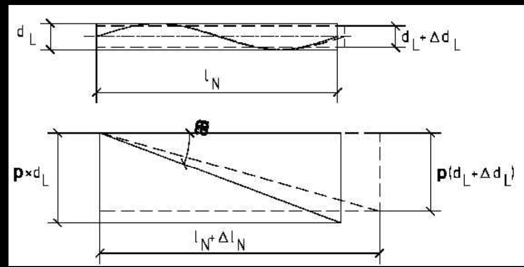
1. Cable Creep



Cable Length

1. Cable Creep

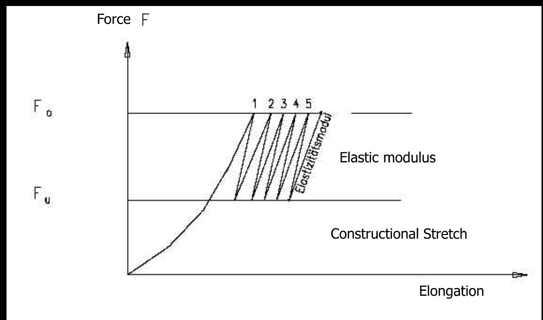
Cable Geometry (setting of the wires)



Cable Length

1. Cable Creep

Pre-stretching/elongation after multiple loadings



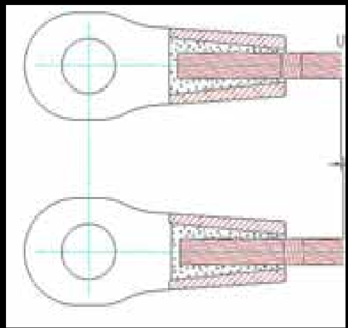
Cable Length

1. Cable Creep

Pre-stretching to minimize creep.

Cable Length

2. Setting of the Cone



Unloaded cable

Setting of the cone

Loaded Cable

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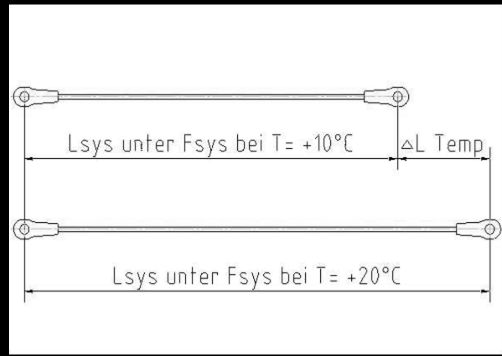
Cable Length

3. Temperature



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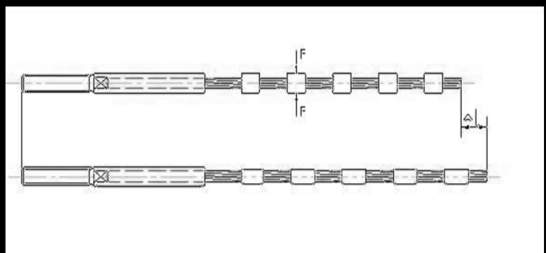
Cable Length

4. Additional Elongation due to Clamping



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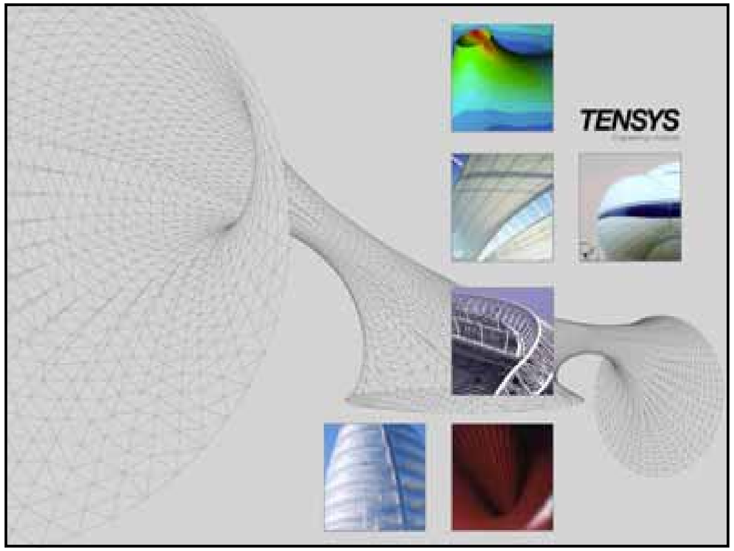
Cable Length

5. Cable Elongation (Strand Modulus)

ΔLelast = (Fsys * Lsys)/(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



ENGINEERING PRINCIPLES OF TENSION MEMBRANE STRUCTURES

DESIGN PROCESS IN TENSION STRUCTURES PROJECT

Peter Lim
Tensys

LSAA

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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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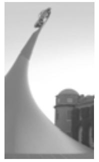
Temporary or permanent

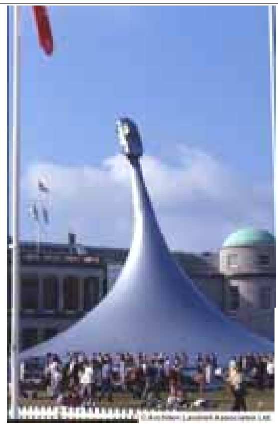
- Temporary structures
  - Short life span for material
  - Less onerous load cases

" the Engineer is able to push the use of the fabric to the limit "



Goodwood Festival of Speed 2001

PVC Membrane



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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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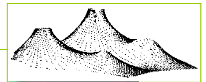
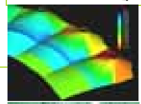
Membrane Engineering : Typical Scope of Work

- "Tensile structure engineering is a unique field. It demands specialist knowledge, techniques and design software"

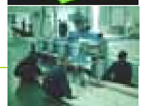
Shape Finding



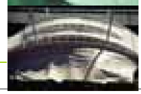
Load Analysis



Fabrication Geometry



Erection Analysis



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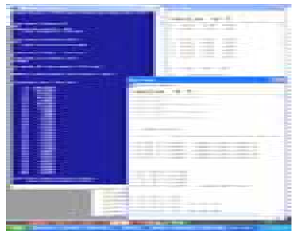
Specialist engineering

- 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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Surface Form Possibilities

- Hypar
- Barrel Vault
- Conic

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Surface Form Possibilities

- Ridge valley system
- Inflated

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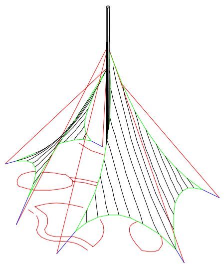
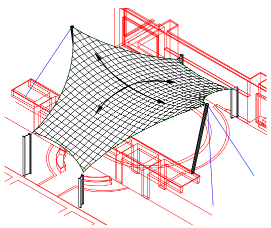
Shape & Form

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





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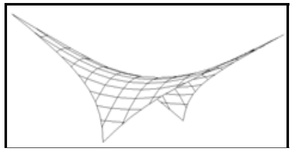
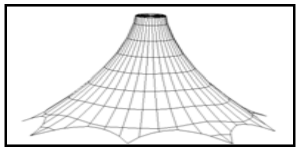
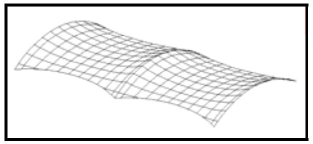
Shape & Form



Hypar



Conic



Barrel Vault

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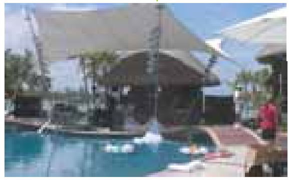
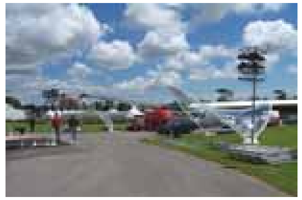
Choice of surface form 1 : Hypar

- 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



Choice of surface form 1: Hypar

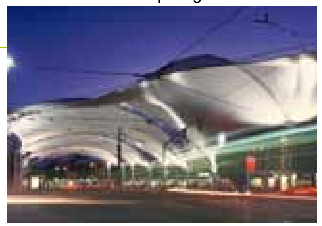
- Classic 'Saddle' shape
- In its most basic form, membrane tensioned between 'saddle' shaped supporting steelwork.



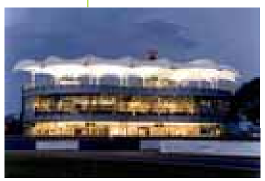
Choice of surface form 2 : Barrel Vault

- Membrane tensioned between two arches with scallop edges

Urban Loritz Platz Vienna



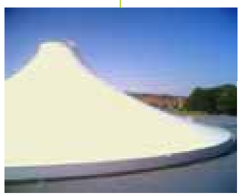
BRDC Clubhouse UK



Hua Shao Yu Ticket Office China

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



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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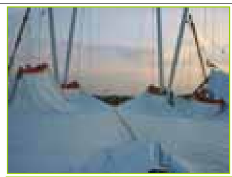
Choice of surface form 4 : Ridge Valley System



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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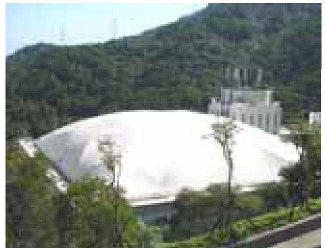
Variations of form : Frames + Domes

Edo Tokyo Museum



Da Kwan Basketball Court, Korea

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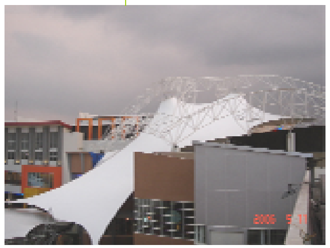
Variations of form : Combinations of forms

Conic, plus ridge valley, plus hypar!



Ridge valley system with membrane pulled over curved support arm.

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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

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Surface Form Possibilities

"The only limitation is your imagination"

- Choice of surface form

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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

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Choice of supporting structure

- Conical membrane
  - Support for central head ring

Supported with column

Suspended

Flying struts

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Choice of supporting structure

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

- Nature of support structure

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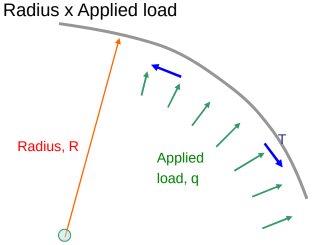
Membrane form finding

“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



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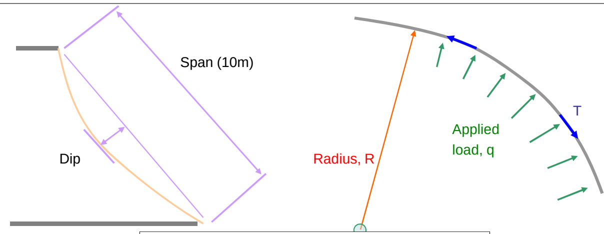
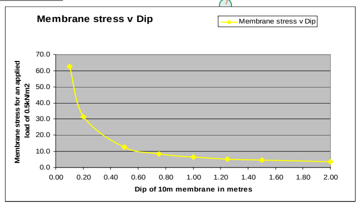
Membrane form finding





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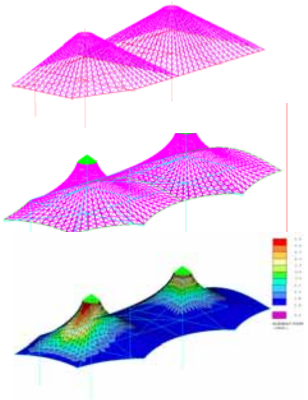
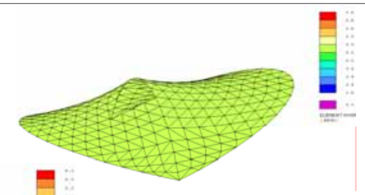
Membrane form finding

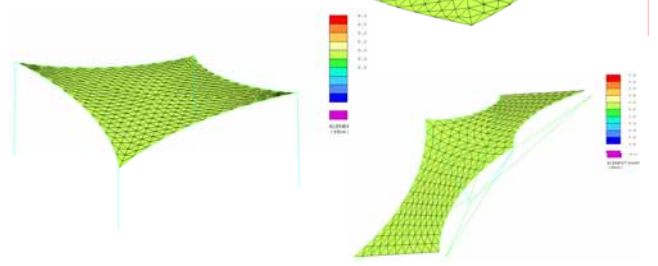
- Tension structures software, normally:
  - FE elements such as triangular elements
  - Cable net equivalent
- Two common methods for form finding
  - Dynamic Relaxation:
    - Application of a series of membrane stresses to the FE mesh surface. Resultant shape found using dynamic relaxation solver.
  - Force Density Methods:
    - A geometry is defined, a stress field is found to maintain equilibrium.
  - Other methods.



Membrane form finding

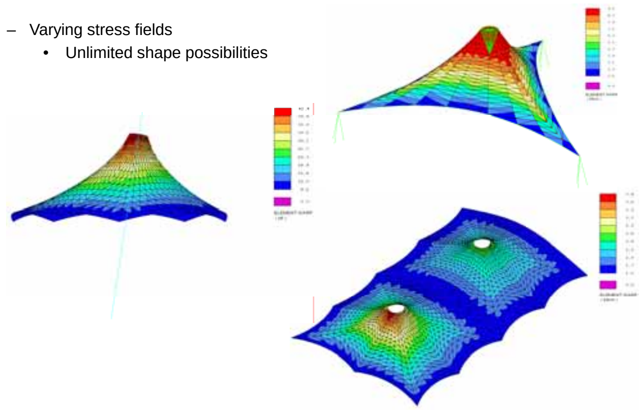
– Uniform stress fields
  - Minimal surface
  - Efficient use of fabric
  - Limited shapes possible



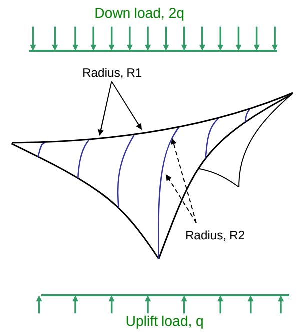


Membrane form finding

– Varying stress fields
  - Unlimited shape possibilities



Membrane form finding



T1 = R1 . 2Q

T2 = R2 . Q → T1 >T2

– Further benefits of varying stress field – potential improvements in fabric grade

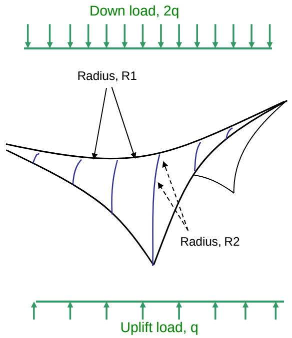
– Consider a basic hypar with a uniform stress field 1:1, i.e. a minimal surface

– Same radius of membrane in each direction, R1=R2

– Down load = 2 x uplift load

– Maximum stress in one direction will be twice the maximum stress in the second direction

Membrane form finding



- NON Uniform stress field, i.e. 1:2, or 2:1. NO longer a minimal surface, i.e. R1 = R2
- For this case, R2 = 2 x R1
- Down load is 2 x uplift loads, but radii have been altered to suit
- EQUAL FABRIC STRESSES IN BOTH DIRECTIONS UNDER LOAD
- MOST EFFICIENT USE OF FABRIC`

– Basics of form finding

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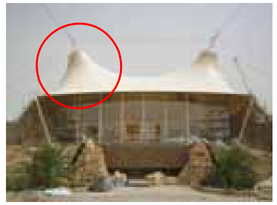
Modelling of supporting structure



- Modelling of supporting structure?

NO

- •Steelwork deflections will have little effect on membrane stresses
- •When considering additional time required to include steelwork in model, little gains in membrane stress reductions.

- YES

- •Flexible structure, movements in supporting structure under load, will relieve membrane stresses.
- •More accurate analysis, lowest membrane stresses

– Support structure and boundary conditions

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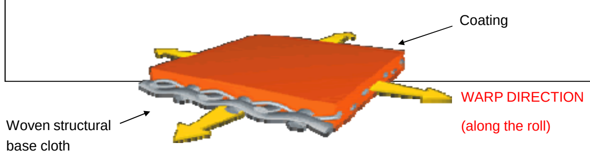
Choice of direction for seam lines

- 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

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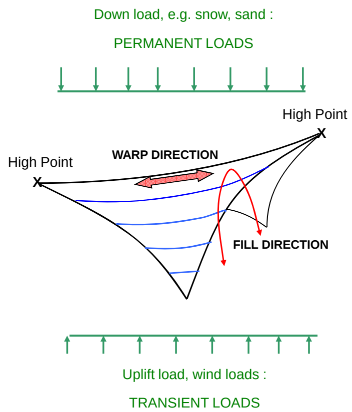
Choice of direction for seam lines



- Warp direction chosen to span from high point to high point. 'Sagging' curvature.
- Fill direction to span low point to low point. 'Hogging curvature'.
- Stiffer, stronger warp direction to carry permanent loads.
- Less stiff fill direction to carry transient wind uplift loads
- Less chance of 'creep' in fabric

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Choice of direction for seam lines - examples

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Choice of direction for seam lines - exceptions

- The above rule for the direction of the warp seams is not set in stone
- There may be exceptions for the following reasons:
  - Architectural / aesthetic reasons
  - Improved cutting pattern efficiency (less seams, longer patterns)
  - Installation method. (preferable to tension the fabric along the fill direction during installing).

    – Choice of seam line direction

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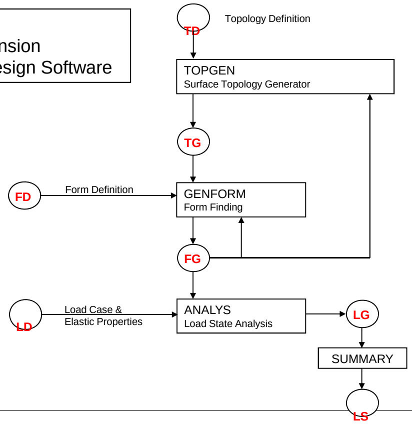
TENSYS inTENS Program Structure

inTENS
Integrated Tension
Structures Design Software



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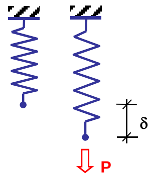
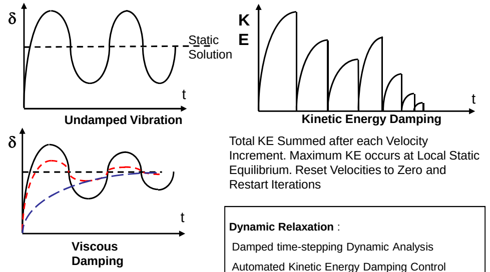
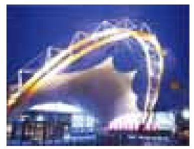
TENSYS inTENS Software : Basis of Dynamic Relaxation



Determination of a Static Solution to Applied Loading by Damping out a Dynamic Application of that Load



Total KE Summed after each Velocity Increment. Maximum KE occurs at Local Static Equilibrium. Reset Velocities to Zero and Restart Iterations



Dynamic Relaxation :
- Damped time-stepping Dynamic Analysis
- Automated Kinetic Energy Damping Control
- Natural Treatment of Large Deformations
- Tolerance of Large Out of Balance Forces
- Storage Requirements Linear with Problem Size
- Full Range of Finite Elements : Membranes, Cables, Struts, Beams
- Clear Physical Analogy and Simple Elements

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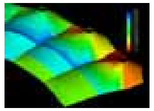
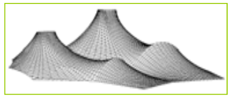
Level of pre-stress





– 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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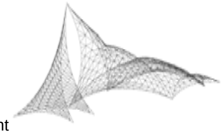
Level of pre-stress



– 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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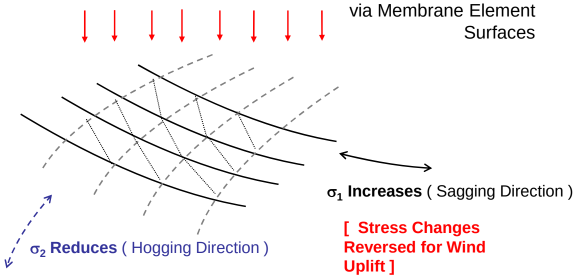
Load Analysis

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



Material Elastic Properties and Selfweight Introduced into Prestress Equilibrium Form

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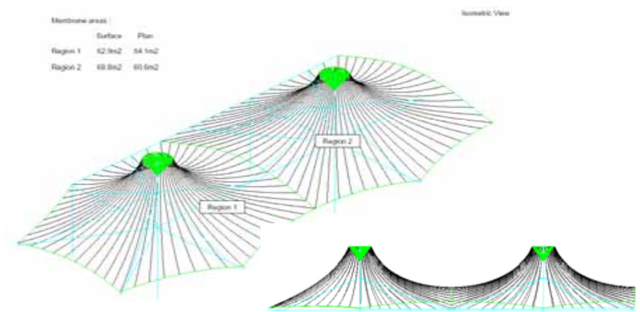
Load analysis – choice of load cases



– Load Analysis
- 'Investigation of the response of the structure to environmental load conditions'
- Load cases determined using appropriate design codes
- Consider typical structure:

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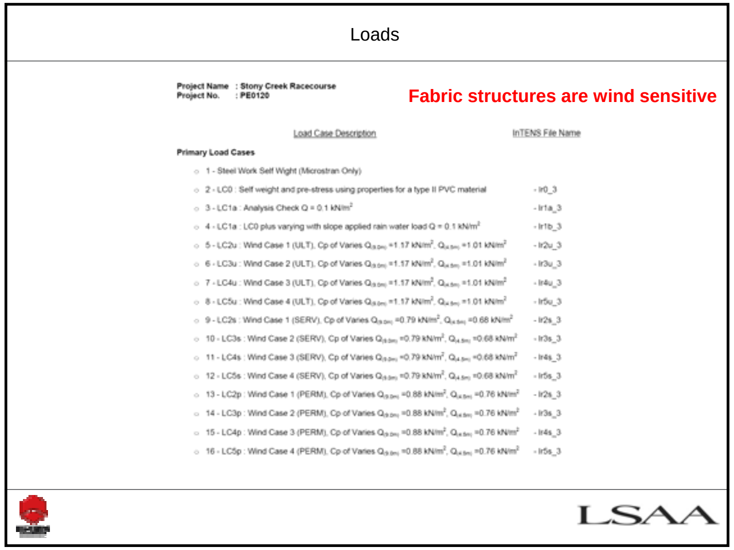
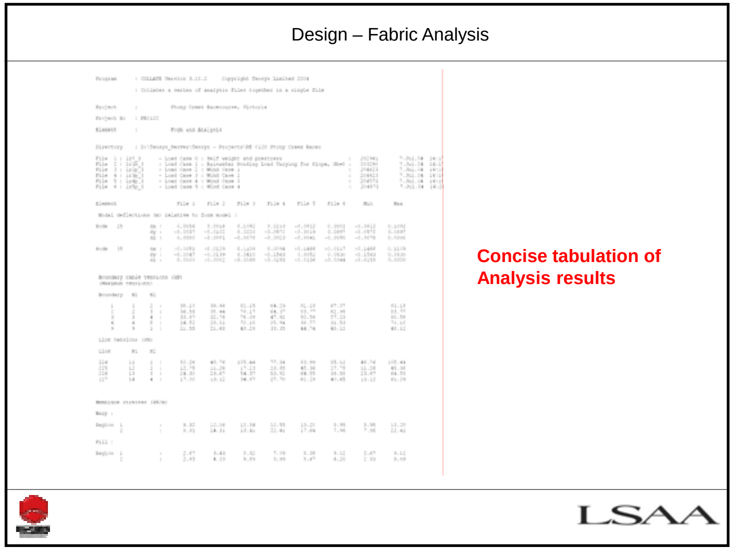
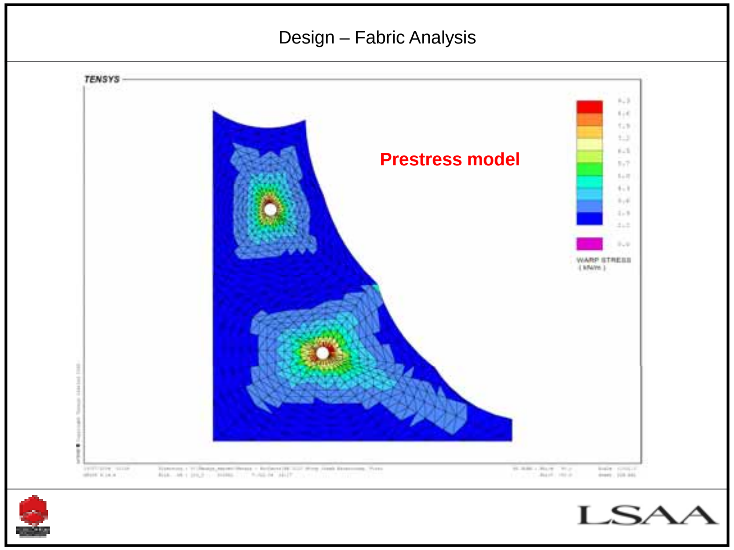
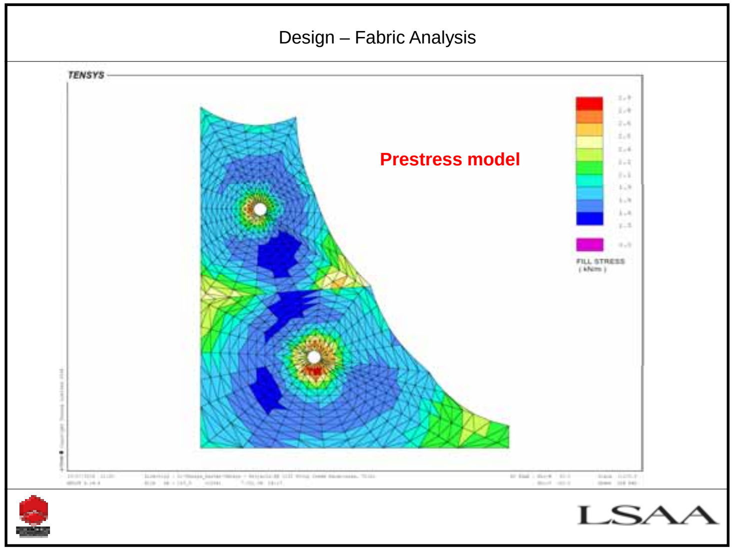
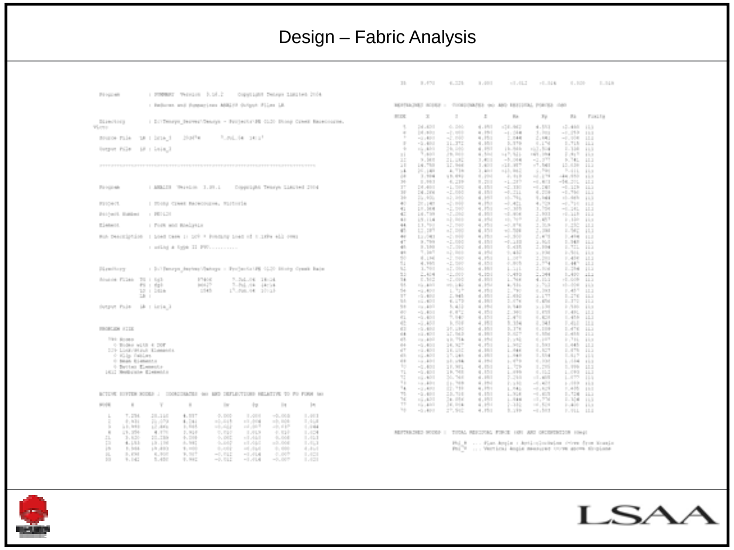
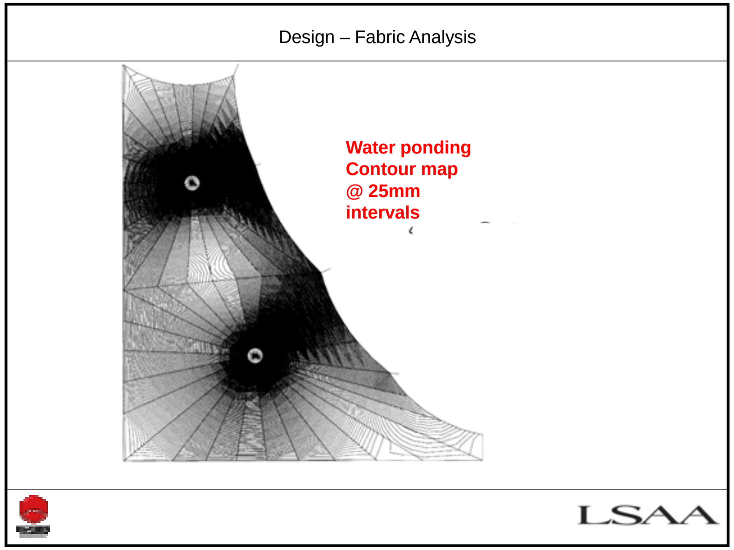

Loads
Project Name : Stony Creek Racecourse
Project No. : PE0120
Fabric structures are wind sensitive
Load Case Description
InTENS File Name
Primary Load Cases
1 - Steel Work Self Wight (Microstran Only)
2 - LC0 : Self weight and pre-stress using properties for a type II PVC material - lr0_3
3 - LC1a : Analysis Check Q = 0.1 kN/m^2 - lr1a_3
4 - LC1a : LC0 plus varying with slope applied rain water load Q = 0.1 kN/m^2 - lr1b_3
5 - LC2u : Wind Case 1 (ULT), Cp of Varies $Q_{(9.0m)}$ =1.17 kN/m^2, $Q_{(4.5m)}$ =1.01 kN/m^2 - lr2u_3
6 - LC3u : Wind Case 2 (ULT), Cp of Varies $Q_{(9.0m)}$ =1.17 kN/m^2, $Q_{(4.5m)}$ =1.01 kN/m^2 - lr3u_3
7 - LC4u : Wind Case 3 (ULT), Cp of Varies $Q_{(9.0m)}$ =1.17 kN/m^2, $Q_{(4.5m)}$ =1.01 kN/m^2 - lr4u_3
8 - LC5u : Wind Case 4 (ULT), Cp of Varies $Q_{(9.0m)}$ =1.17 kN/m^2, $Q_{(4.5m)}$ =1.01 kN/m^2 - lr5u_3
9 - LC2s : Wind Case 1 (SERV), Cp of Varies $Q_{(9.0m)}$ =0.79 kN/m^2, $Q_{(4.5m)}$ =0.68 kN/m^2 - lr2s_3
10 - LC3s : Wind Case 2 (SERV), Cp of Varies $Q_{(9.0m)}$ =0.79 kN/m^2, $Q_{(4.5m)}$ =0.68 kN/m^2 - lr3s_3
11 - LC4s : Wind Case 3 (SERV), Cp of Varies $Q_{(9.0m)}$ =0.79 kN/m^2, $Q_{(4.5m)}$ =0.68 kN/m^2 - lr4s_3
12 - LC5s : Wind Case 4 (SERV), Cp of Varies $Q_{(9.0m)}$ =0.79 kN/m^2, $Q_{(4.5m)}$ =0.68 kN/m^2 - lr5s_3
13 - LC2p : Wind Case 1 (PERM), Cp of Varies $Q_{(9.0m)}$ =0.88 kN/m^2, $Q_{(4.5m)}$ =0.76 kN/m^2 - lr2s_3
14 - LC3p : Wind Case 2 (PERM), Cp of Varies $Q_{(9.0m)}$ =0.88 kN/m^2, $Q_{(4.5m)}$ =0.76 kN/m^2 - lr3s_3
15 - LC4p : Wind Case 3 (PERM), Cp of Varies $Q_{(9.0m)}$ =0.88 kN/m^2, $Q_{(4.5m)}$ =0.76 kN/m^2 - lr4s_3
16 - LC5p : Wind Case 4 (PERM), Cp of Varies $Q_{(9.0m)}$ =0.88 kN/m^2, $Q_{(4.5m)}$ =0.76 kN/m^2 - lr5s_3

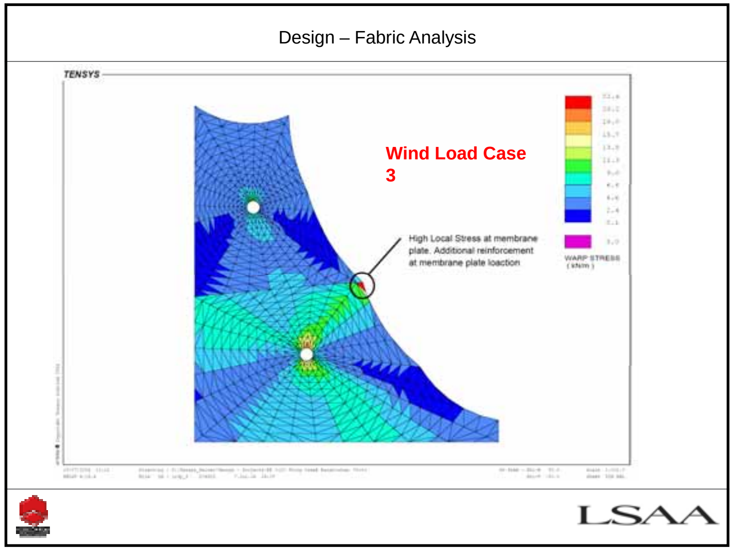

Design – Fabric Analysis
Concise tabulation of Analysis results

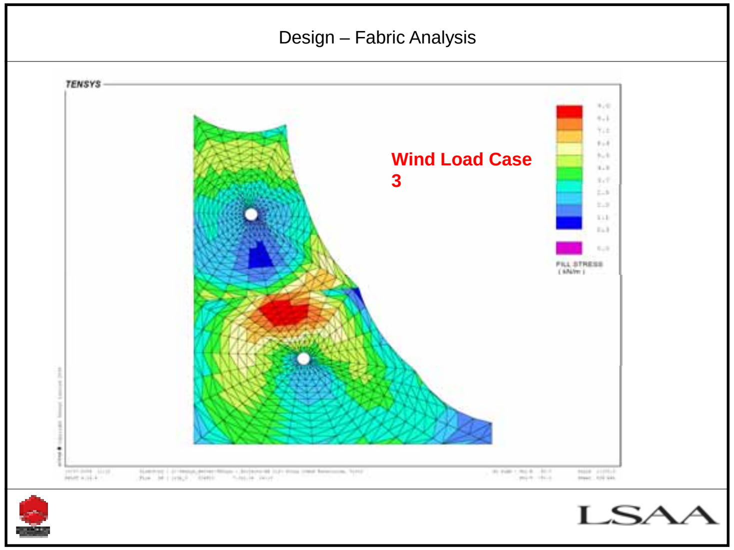

Design – Fabric Analysis
TENSYS
Prestress model
WARP STRESS
(kN/m)


Design – Fabric Analysis
TENSYS
Prestress model
FILL STRESS
(kN/m)


Design – Fabric Analysis
LSAA


Design – Fabric Analysis
Water ponding
Contour map
@ 25mm
intervals
LSAA


Design – Fabric Analysis
TENSYS
Wind Load Case
3
High Local Stress at membrane plate. Additional reinforcement at membrane plate loaction
WARP STRESS
(kN/m)
LSAA


Design – Fabric Analysis
TENSYS
Wind Load Case
3
FILL STRESS
(kN/m)
LSAA

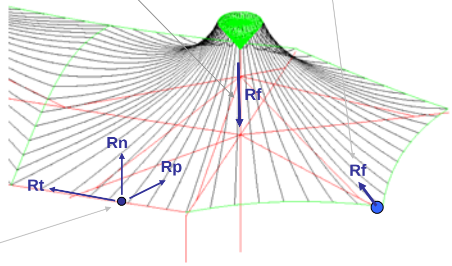
Design of supporting structure

- Examples of reaction forces for use by structural engineer

Reaction thrust forces in the mast

Reaction forces at fixed points (for design of support structure)

Reaction forces along fixed lines
- in the line plane of the connection lines
- perpendicular to the connection line
- Tangential forces, along the connection line



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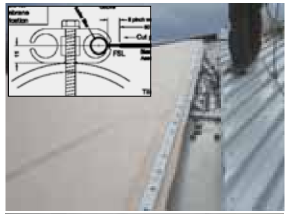
Connection details

- 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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Connection details

- Fabric may creep over time (depends on choice of fabric)
- Re-tensioning capability may be built into connection details

- Support structure designed
- Fabric connection details designed

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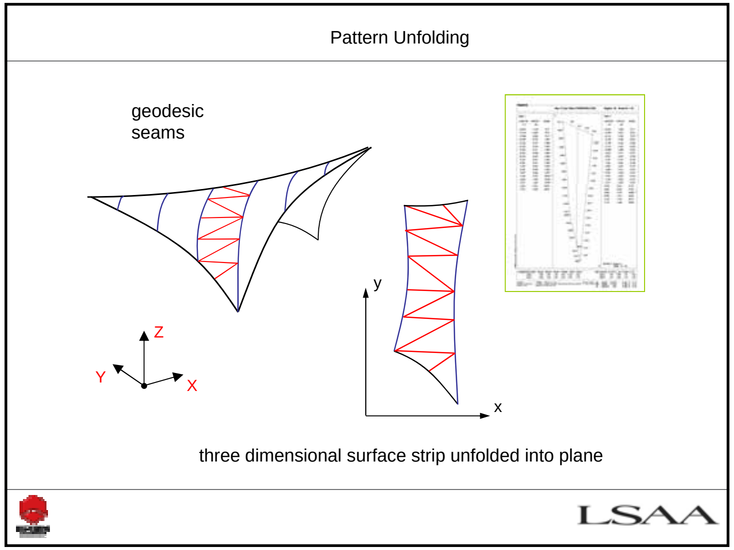
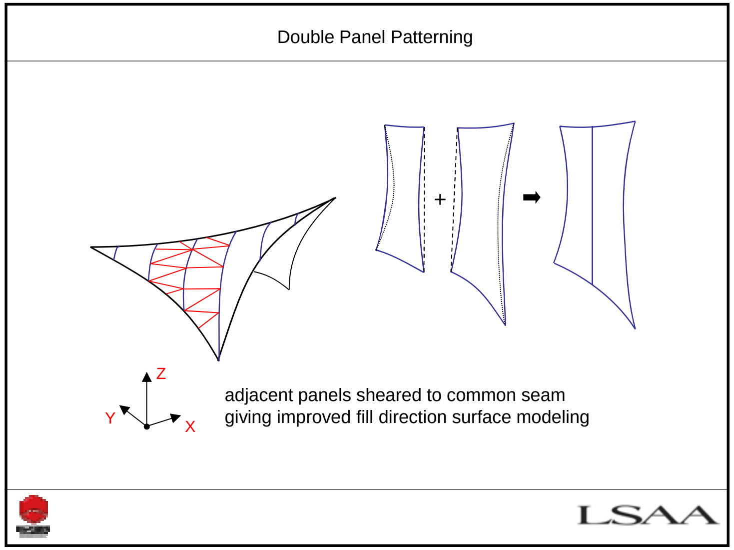
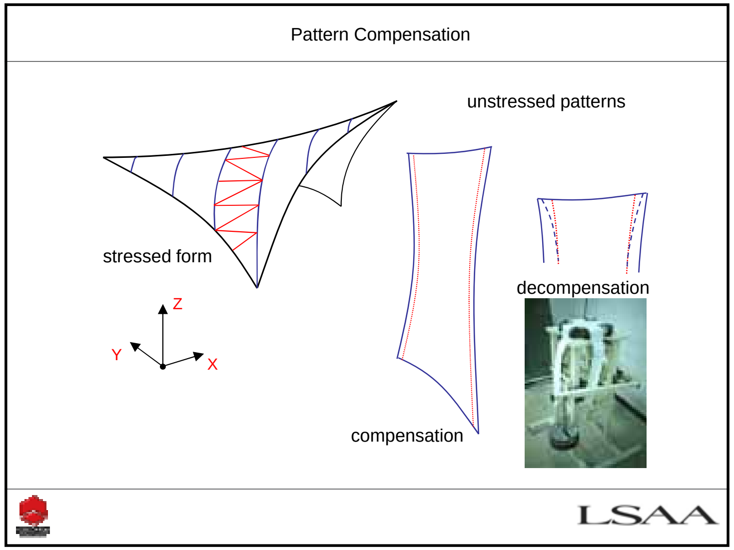
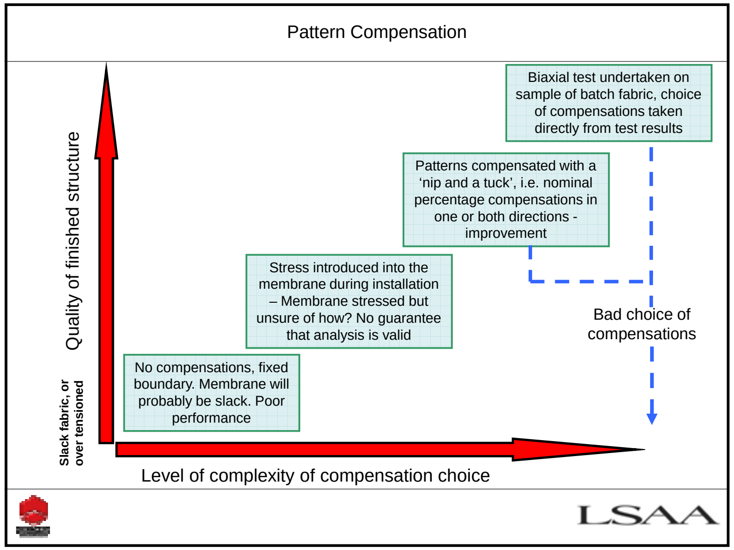
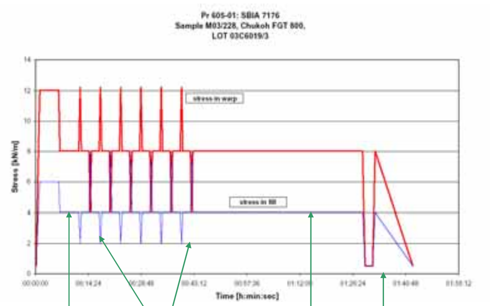

Pattern Unfolding
geodesic seams
Z
Y
X
y
x
three dimensional surface strip unfolded into plane
LSAA


Double Panel Patterning
+
Z
Y
X
adjacent panels sheared to common seam giving improved fill direction surface modeling
LSAA


Pattern Compensation
unstressed patterns
stressed form
Z
Y
X
decompensation
compensation
LSAA


Pattern Compensation
Quality of finished structure
Slack fabric, or over tensioned
Biaxial test undertaken on sample of batch fabric, choice of compensations taken directly from test results
Patterns compensated with a 'nip and a tuck', i.e. nominal percentage compensations in one or both directions - improvement
Stress introduced into the membrane during installation – Membrane stressed but unsure of how? No guarantee that analysis is valid
No compensations, fixed boundary. Membrane will probably be slack. Poor performance
Bad choice of compensations
Level of complexity of compensation choice
LSAA

Pattern Compensation – Biaxial Test



300mm to 500mm square sample

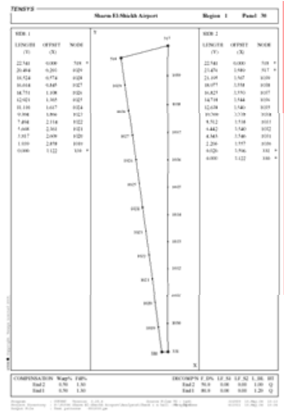
Load cycling

Pre-stress level

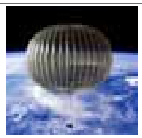
'Hold' period

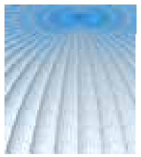
'Unloaded' stage

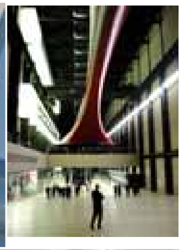
Fabrication – Cutting Pattern Output



Conclusion







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Fabrication, Construction and Installation Processes

David McCready

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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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Example of mis-alignment at edge

PTFE Glass panel bundled for shipping

Robina Stadium – fabric handling.

Robina Stadium – membrane transport

Welding seams on flashing using hand tacker Robina Stadium

Robina Stadium – over flashing.

Robina Stadium

Novel temporary "access platform" Robina Stadium

Specialised handling trough – Robina Stadium

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Rope access to Robina stadium flashing works.

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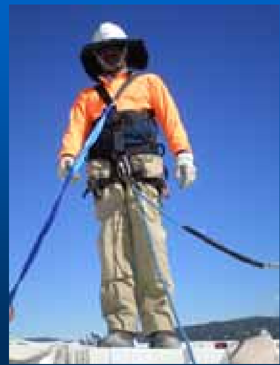
Robina Stadium – rope access.



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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.

RAS – Melbourne – ground activity.

RAS – Melbourne – lifting pods aloft.

RAS – Melbourne – Steelwork stood and guyed off.

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 – mast base after finishing

RAS – Melbourne - interior.

MSAC Swimming Pool _ Melbourne – crawl space scaffold access

Mak Max - Brisbane

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

MSAC – Melbourne – panel being spread.

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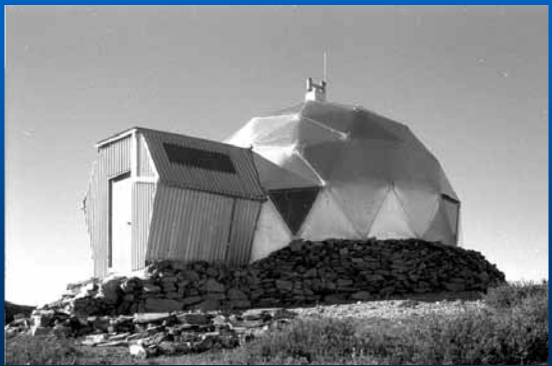
Future Directions for Lightweight Structures

Peter Kneen

Look at the Past, Present ...

- Some past lightweight structures.
- Changing technology
  - Computers – analysis
  - Computers – pre & post processing
  - Visualization
  - Virtual structures

Spaceframes

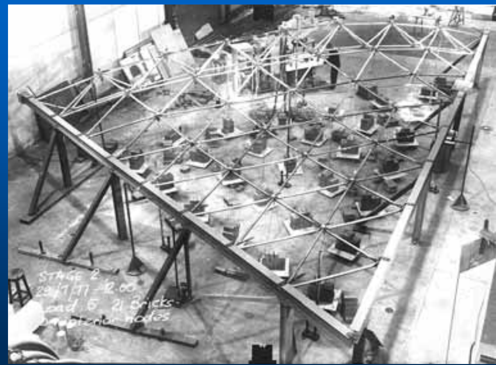


Sao Paulo

Computing 1968

EA LSAA Engineering Principles of Tension Membrane Structures

Prototypes



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Early Membrane Structures

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30 Years ago

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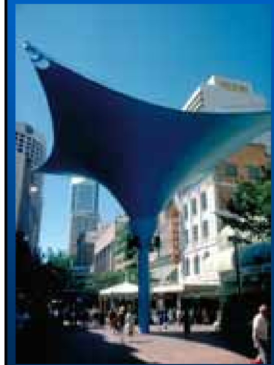
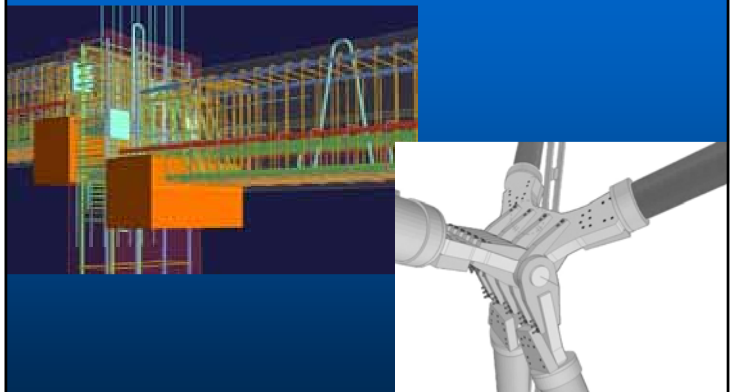
Advances in details



Computational Advances

- Virtual memory
- Graphics monitors
- FEA – composites, non linear ...
- Internet, email
- PCs, Laptops
- Data interchange standards
- 3D models, BIM, CAD/CAM

Current states

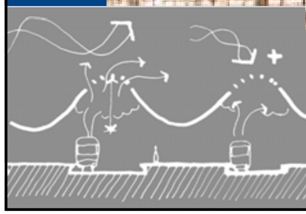


Other Advances

- CFD – Computational Fluid Dynamics
- Scanning / data logging / barcodes / remote sensing
- Space race advances
- Mobile phones+ GPS+

Lightweight Structures - Present

- Examples:
  - Eden Project
  - Southern Cross Station
  - Water Cube
- Common features:
  - Interesting geometry
  - Create / control internal environment
  - Use of computer technology



Future direction ???

- Environmental changes
- Sustainable use of energy
- More efficient infrastructure
- Increased urban density
- Decrease use of cars / roads
- Geometry remains a fascination
- Robotics, GPS, Water/energy harvesting

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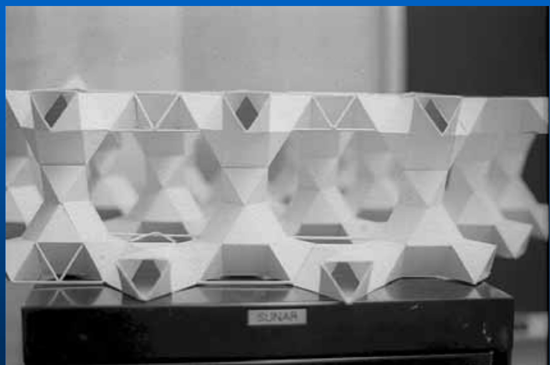
1970 Studies with Prof Burt



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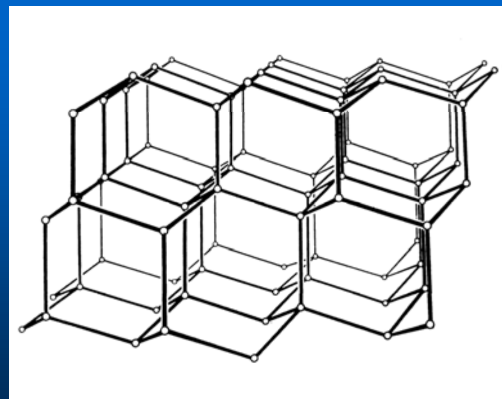

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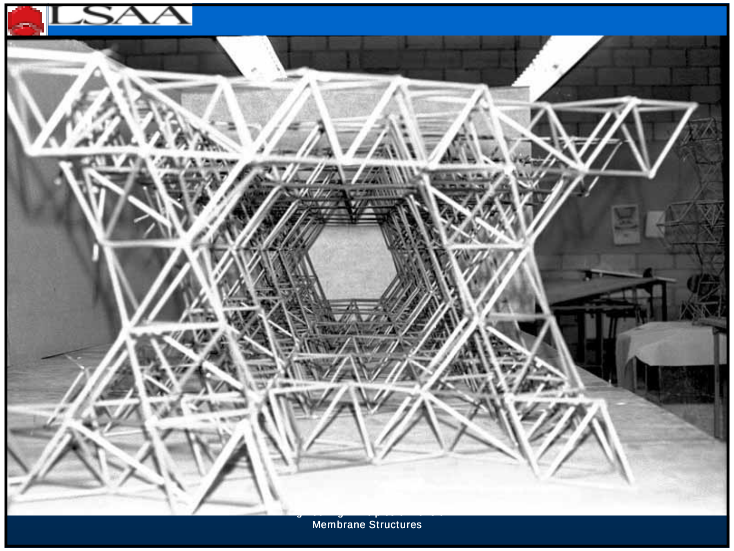
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Membrane Structures


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Membrane Structures