



Learning by making: academic experiences on the design and production of tension structures

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Lay-out of this presentation:

- ***basic ideas on tension structures***
- ***examples on real membrane structures, models and prototypes***
- ***Further comments***



Taut Structures (Tension Structures):

“those that require their elements to be **taut**, instead of **slack** or **wrinkled**, to work properly.



slack

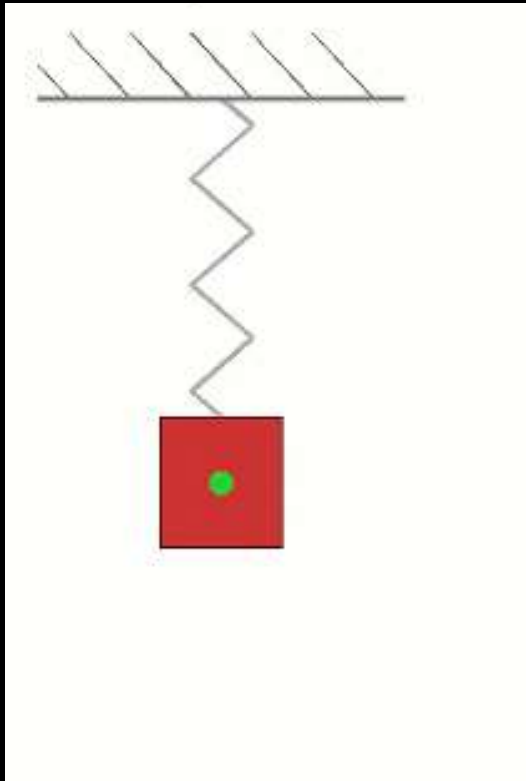


wrinkled



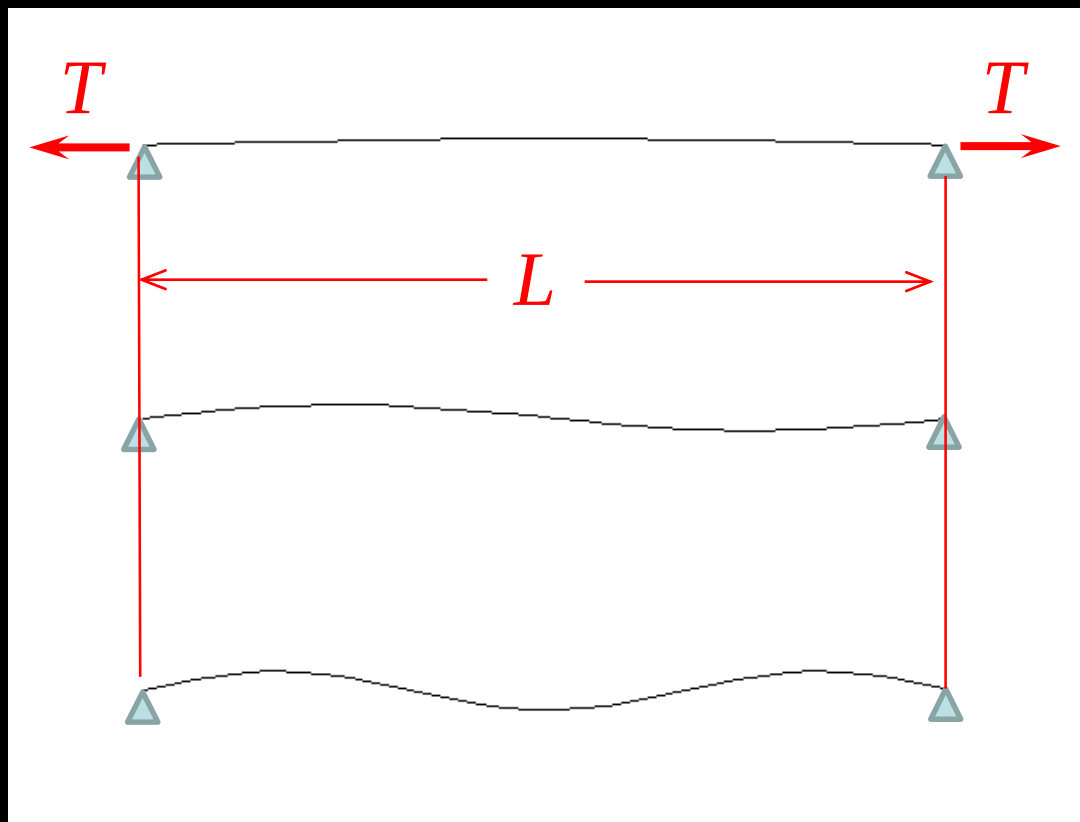
taut

A spring-mass system:



$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

A vibrating string:

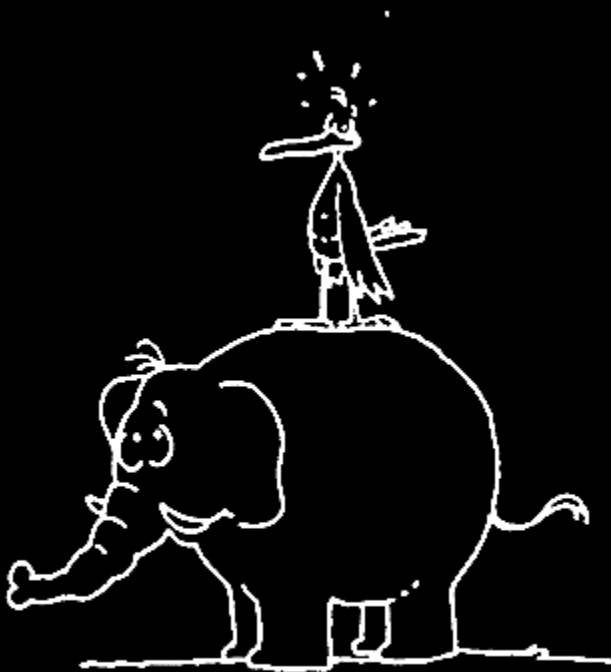


$$f = n\pi \sqrt{\frac{\left(\frac{T}{L}\right)}{m}}$$

‘geometric stiffness’

$$k_g \sim \frac{T}{L}$$

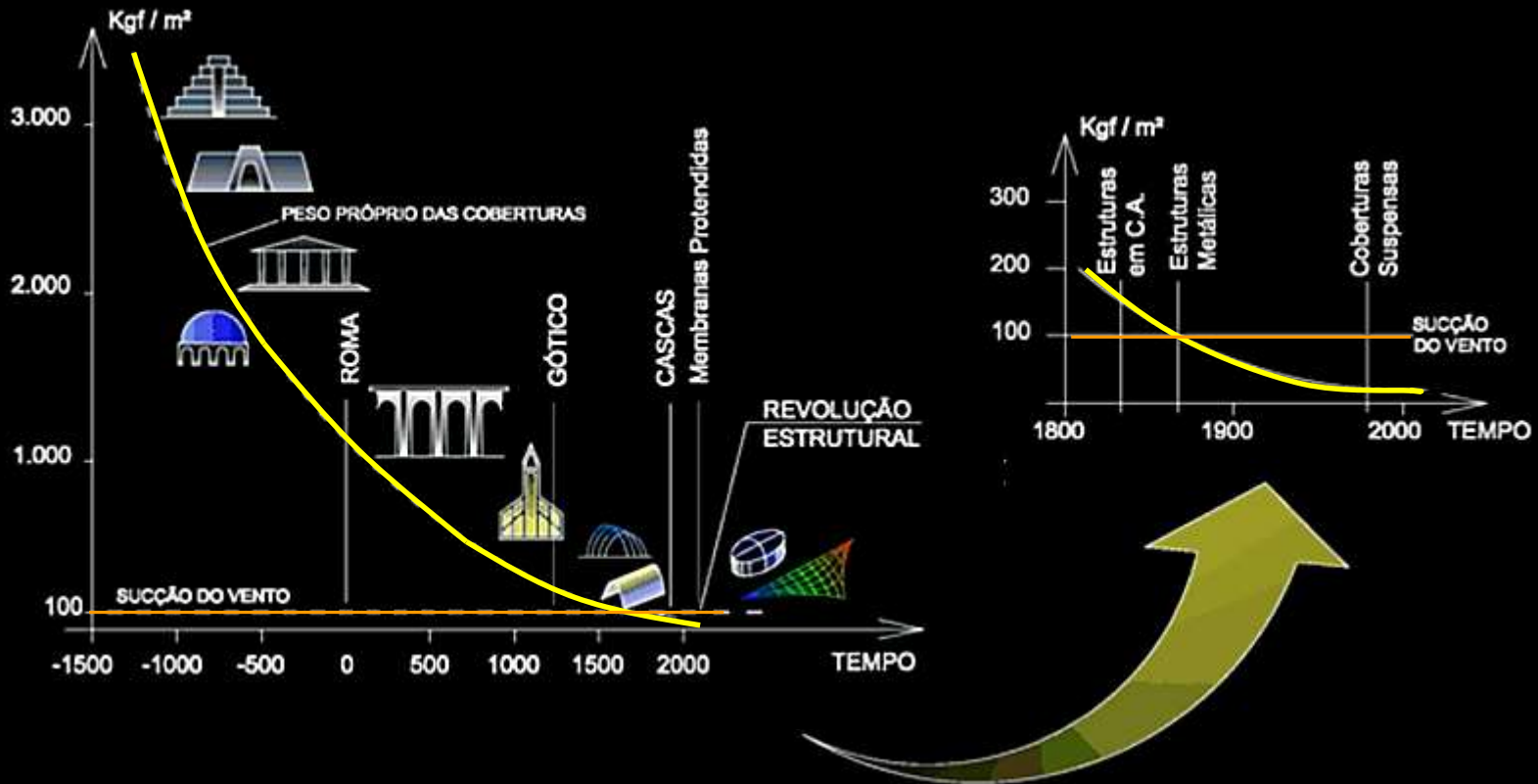
Taut Structures are light structures:



'Supporting weight << supported weight'

Drawing by Enzo Pinto, Naples, 1985.

Taut Structures are light structures:



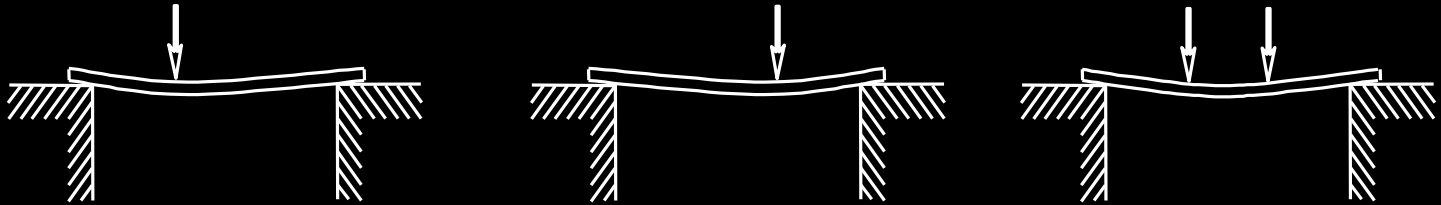
Adapted from R. Serger, "Structures nouvelles in architecture", in Cahiers du centre d'estudes architecturales, n. 1, 1967, p. 42.

“Light structures, structures of light”

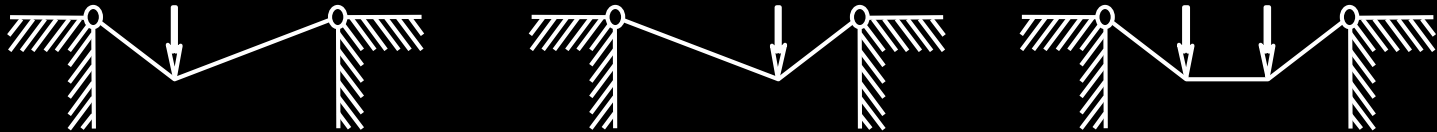
Horst Berger



Taut Structures are 'flexible':



(a) a stiff 'structure' , such as a beam, does not change drastically its shape, when loading varies



(b) A 'flexible' structure, such as a cable, can change drastically its shape, when loading varies

Taut structures must comply to funicular shapes:

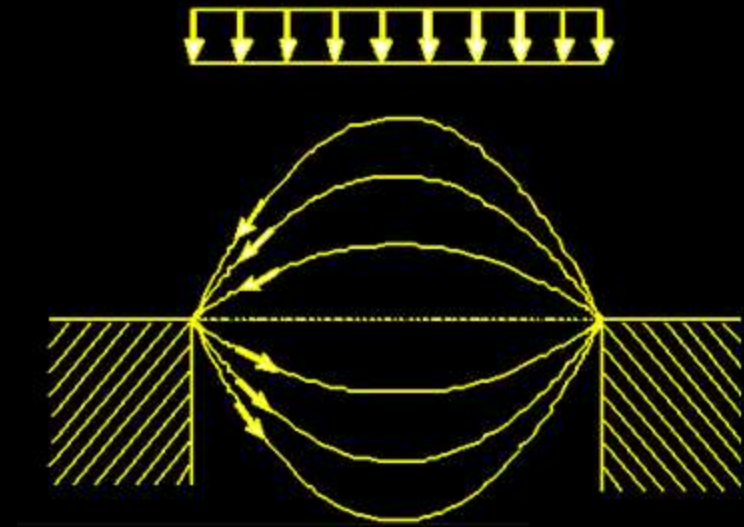
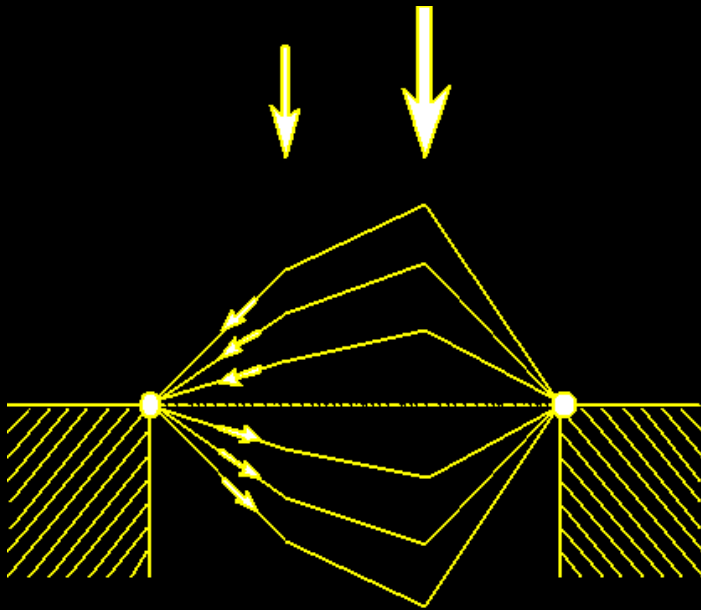
Those that equilibrate a set of loads, without bending



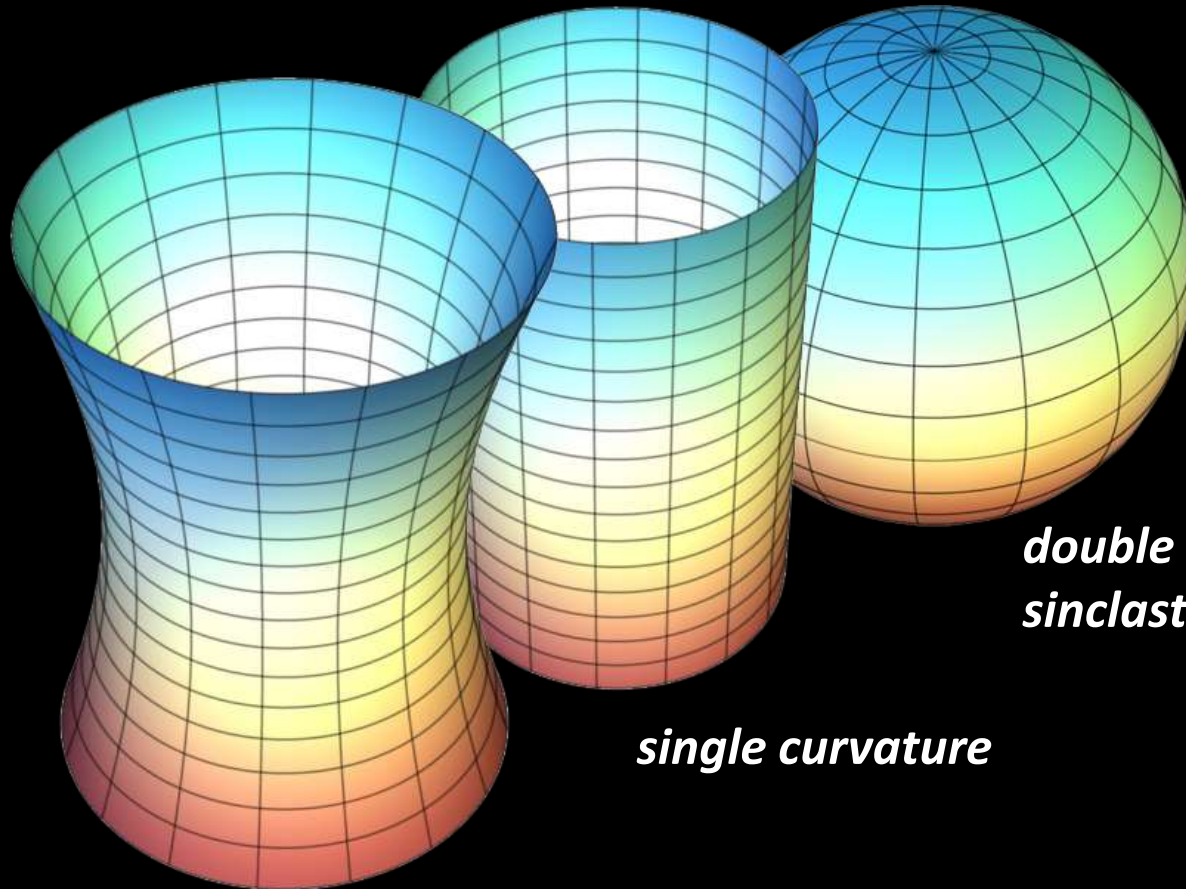




Each load pattern has an associated family of funicular shapes:



Membranes and cable nets usually comply to single or double curvature surfaces:

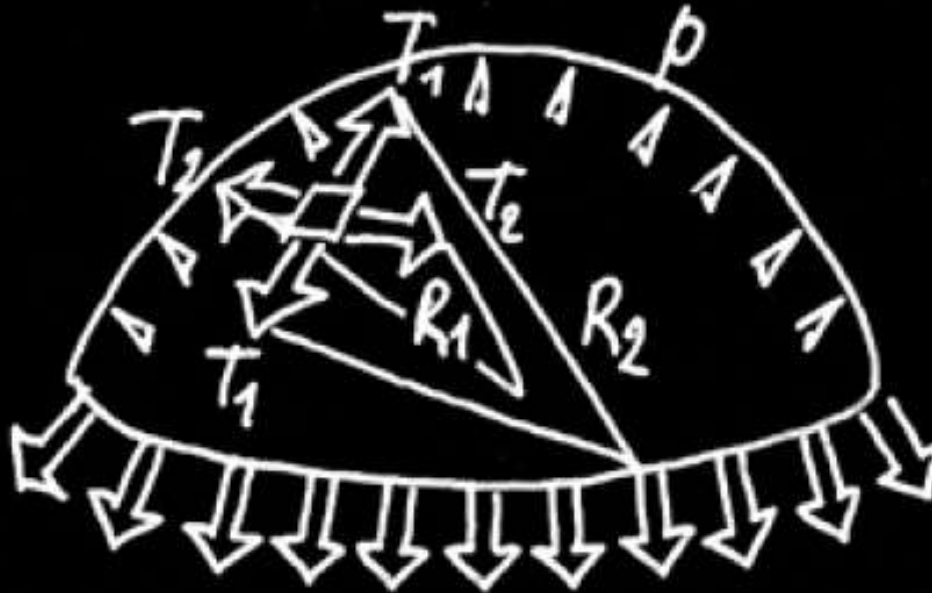


***double curvature,
anticlastic***

single curvature

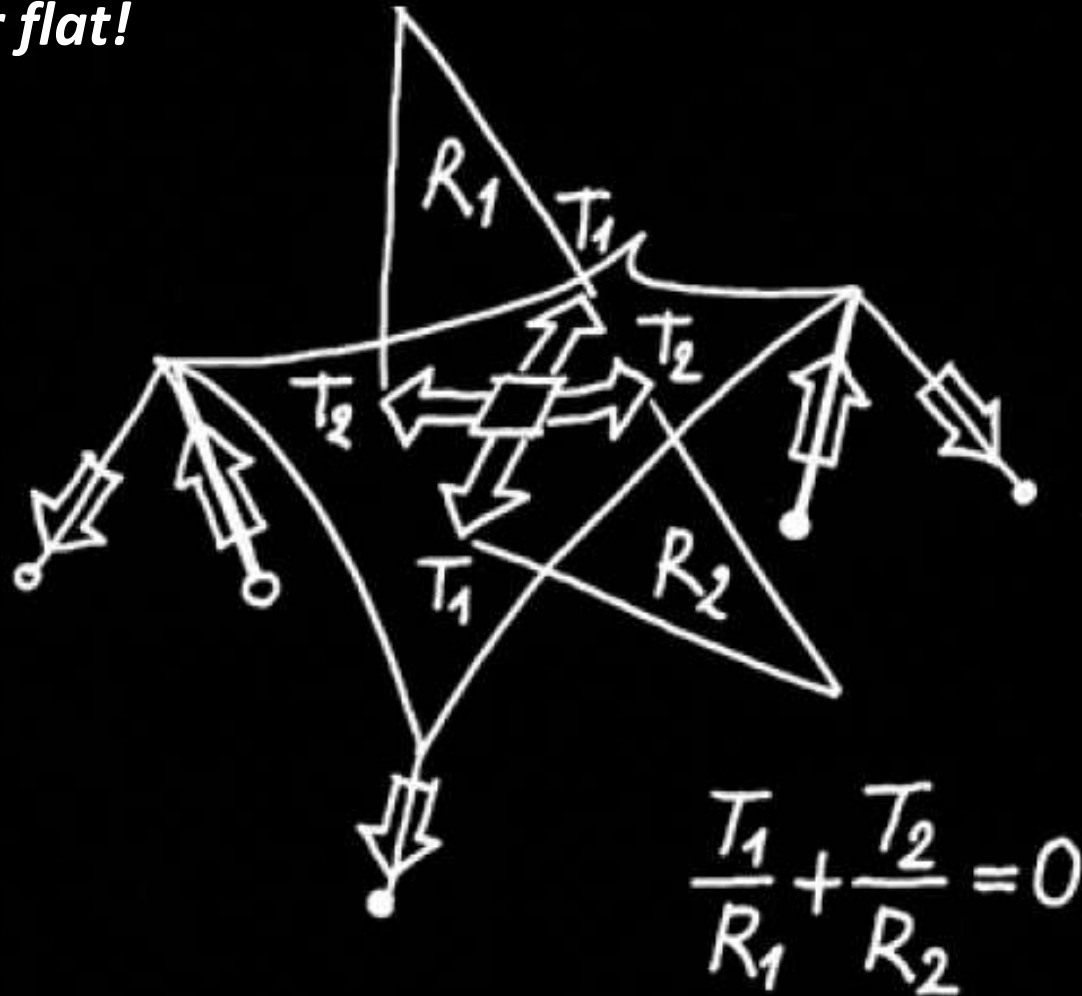
***double curvature,
synclastic***

Pneumatic membranes are commonly sinclastic:



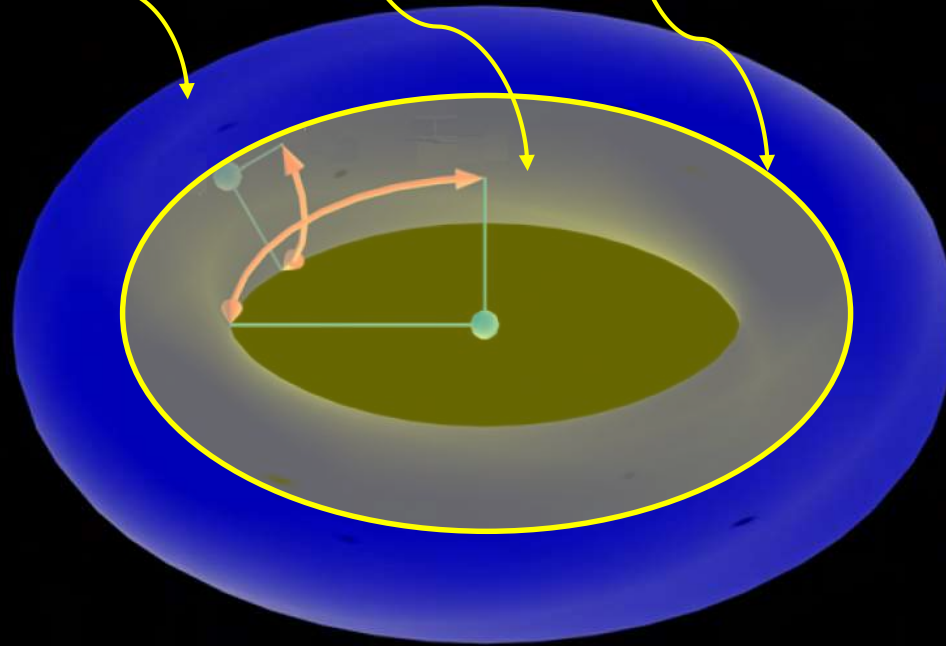
$$\frac{T_1}{R_1} + \frac{T_2}{R_2} = p$$

But self-stressed flexible membranes are always anticlastic or flat!

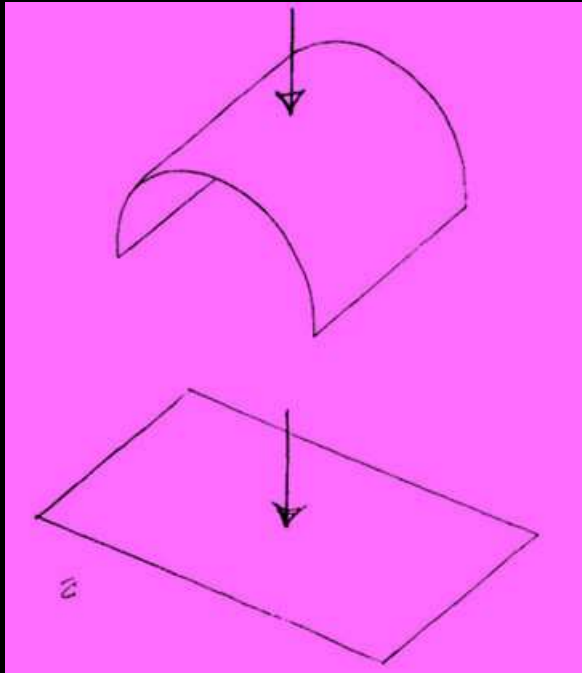


Minimal surfaces are associated to uniform isotropic stress fields, thus $T_1=T_2$ and $R_1=-R_2$ and their mean curvature is zero everywhere!

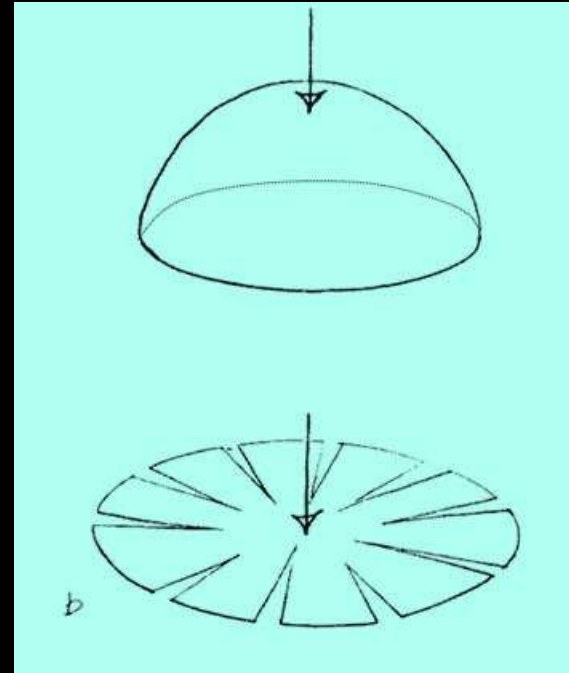
***Pneumatic structures might display
sinclastic, anticlastic and single curvature regions:***



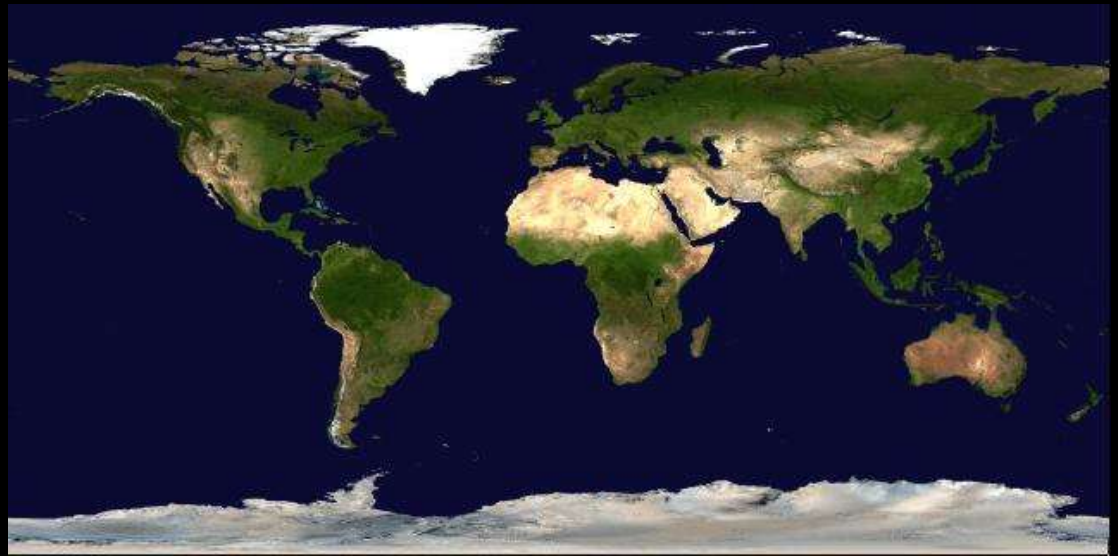
Planification



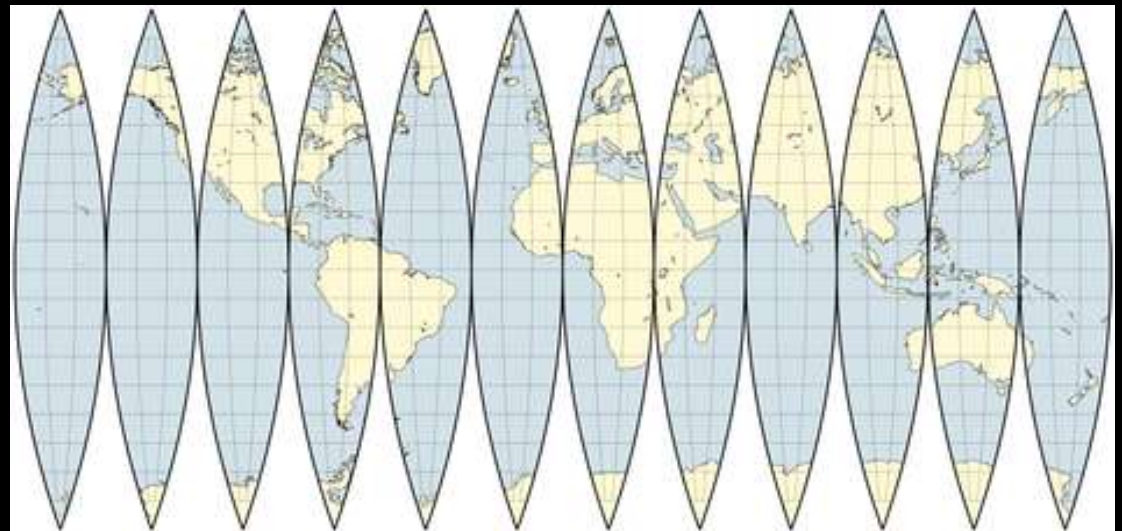
Single curvature surfaces can be flattened without distortion;



Double curvature surfaces undergo distortion due to flattening



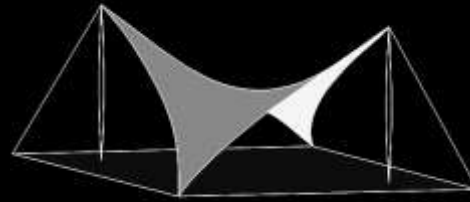
Mercator projection



A gore map using Apian's first projection.

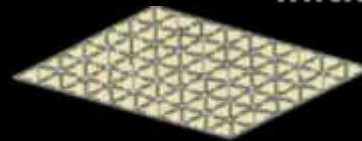
Taut Structures Design Process

ARCHITECTURAL INTENTION:

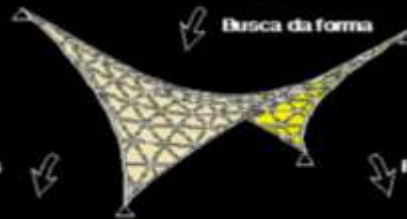


PROJECT / ANALYSIS:

Initial, non-viable shape



Shape Finding

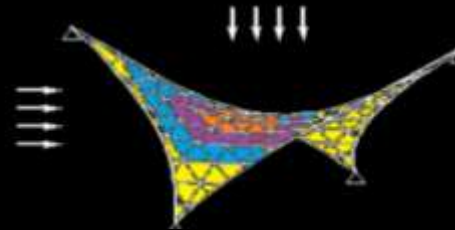


Final, viable shape

Determinação dos padrões de corte

Resposta aos carregamentos

Patterning:



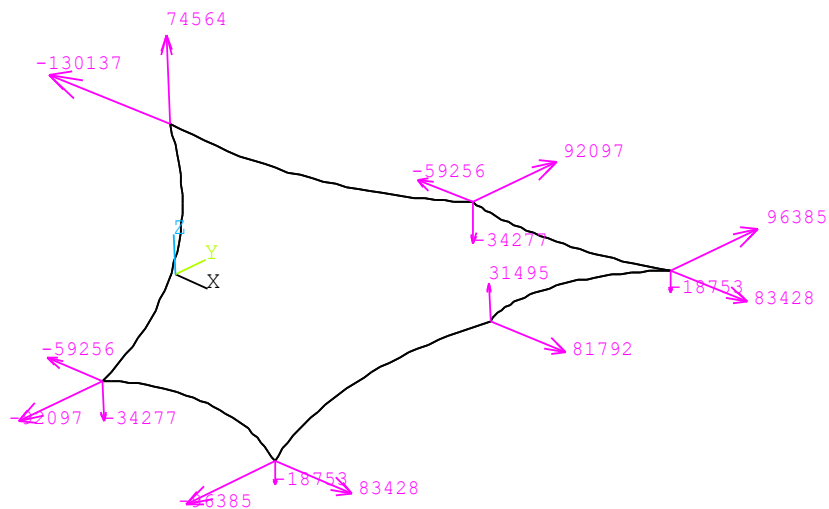
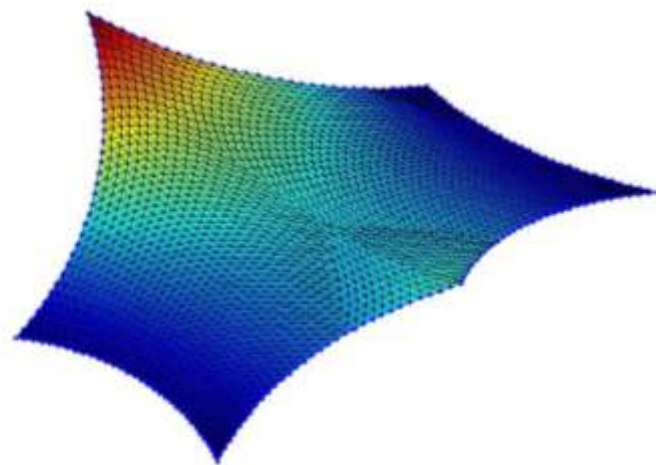
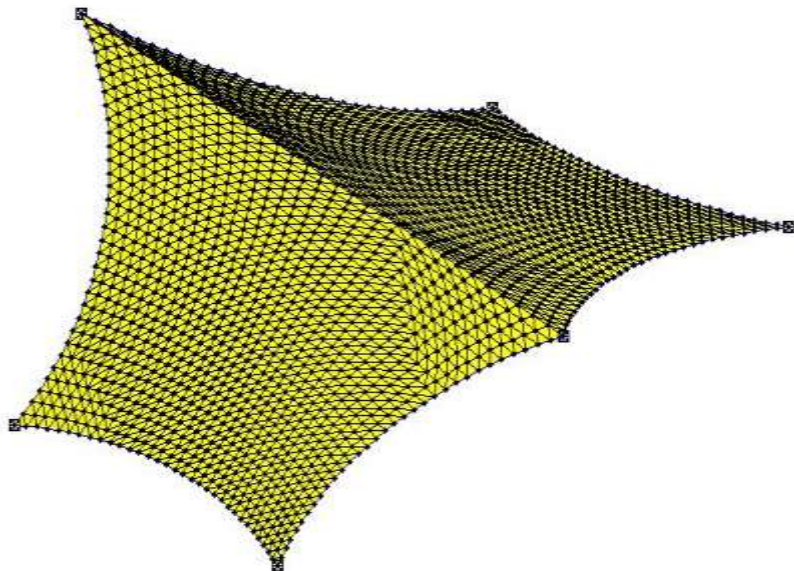
Load analysis

DESIGN SOLUTION:

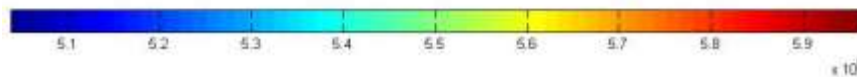
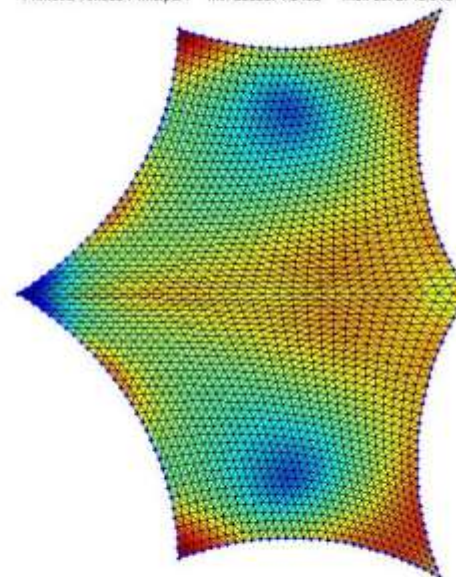


**The membrane roof of the “Memorial dos Povos”
of Belém do Pará (2006)**

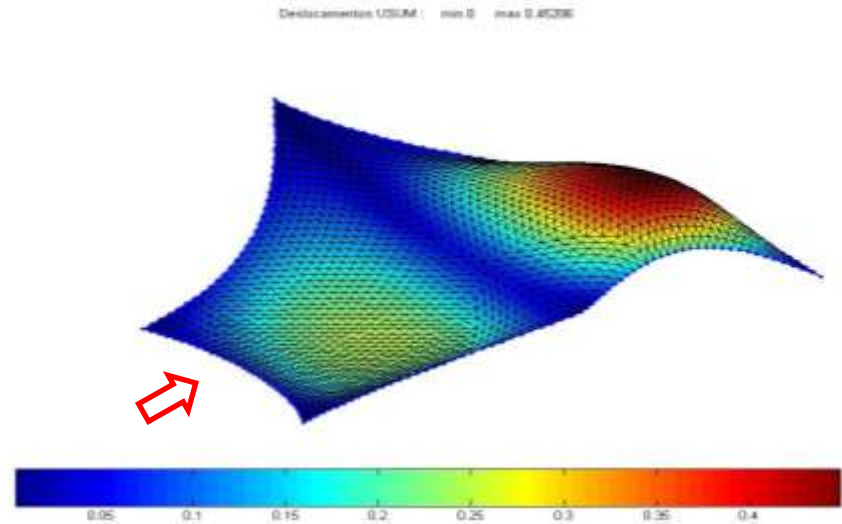
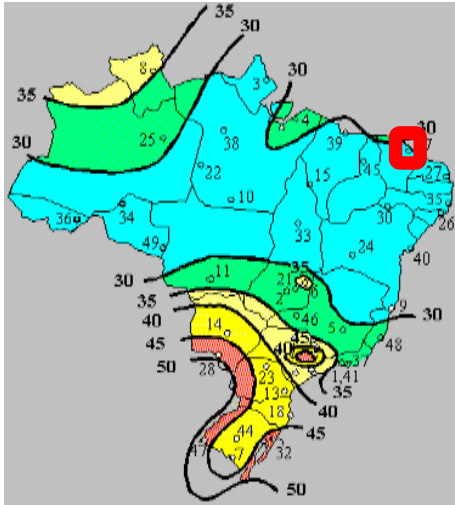




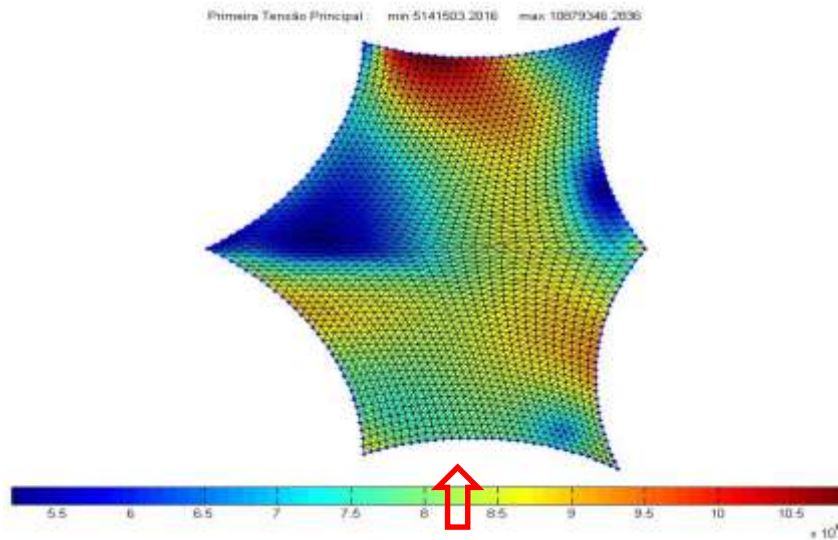
Primeira Tensão Principal : min 5330574.8403 max 5972740.9101



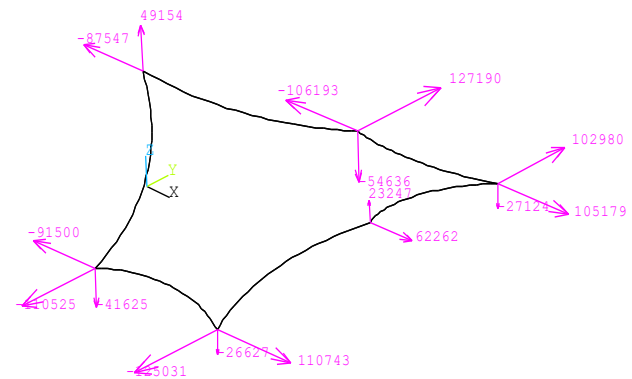
Response under wind loads



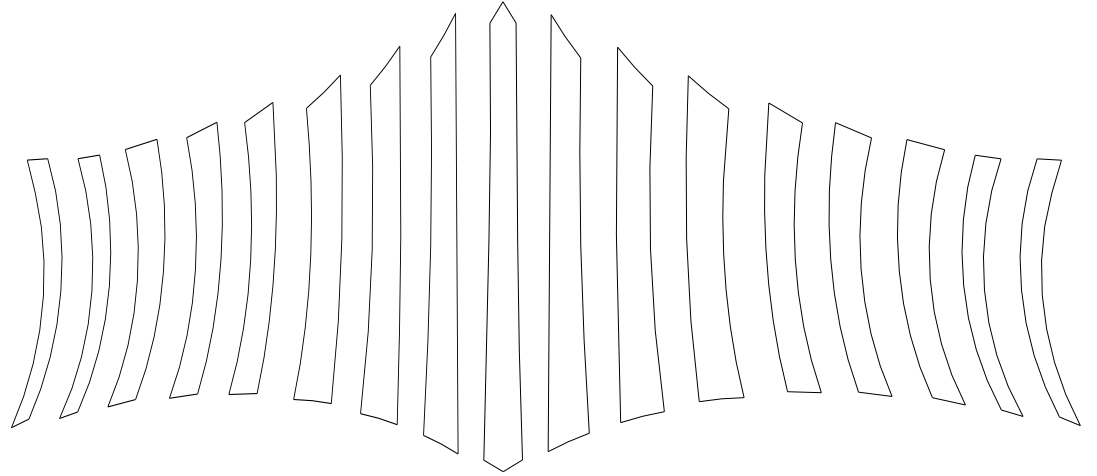
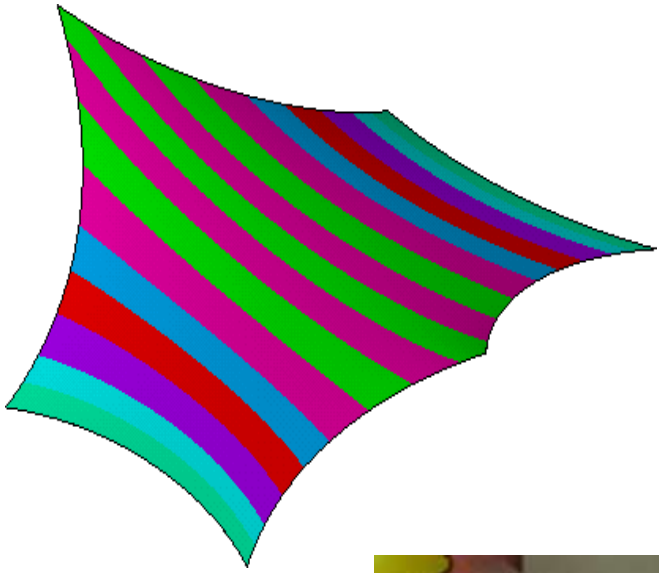
*displacement norms,
for the Y-wind load case*



*Maximum 1st principal stresses
(S1) for the Y-wind load case*



Cutting patterns



Fabric 1:50 model



Fabric 1:10 model

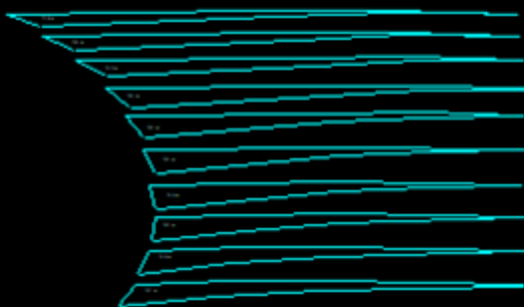
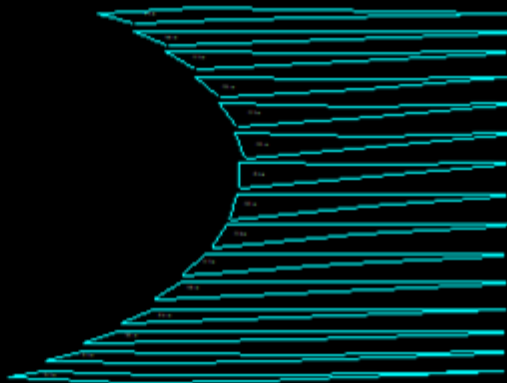
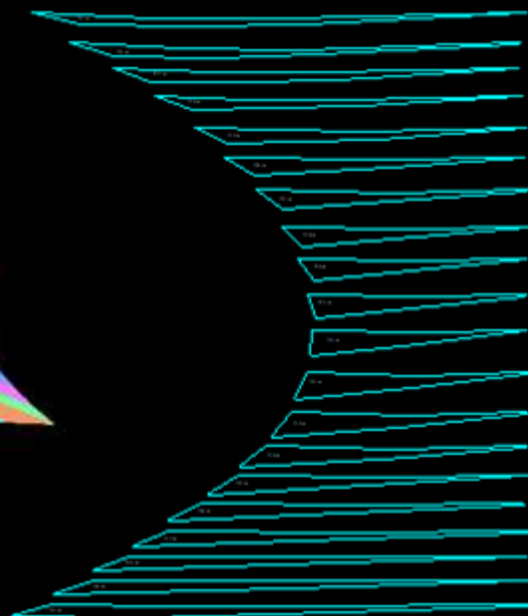
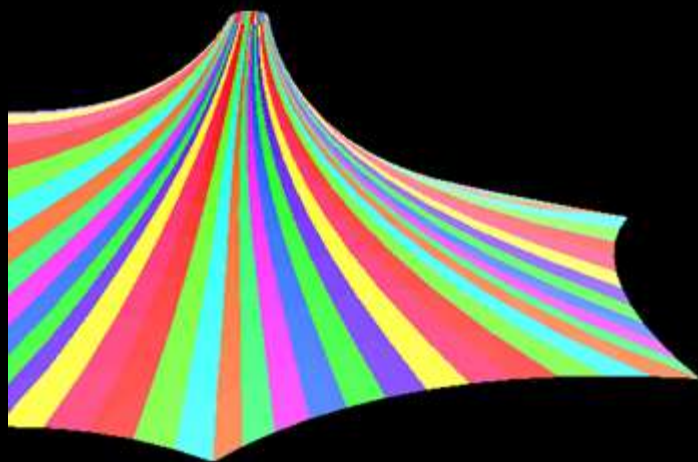
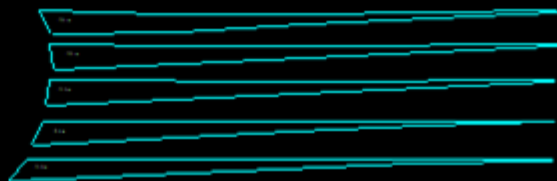
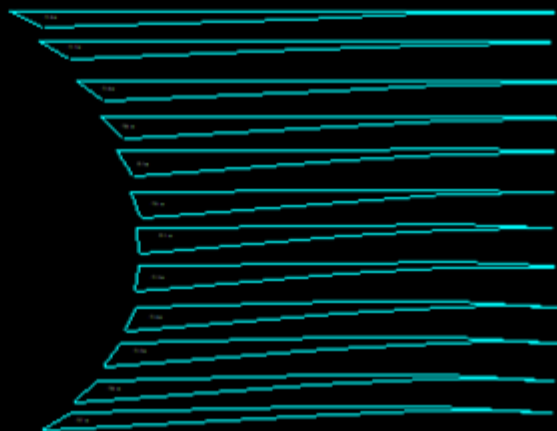






***Baptist Church of Fortaleza
at inauguration, Nov 27, 2003***





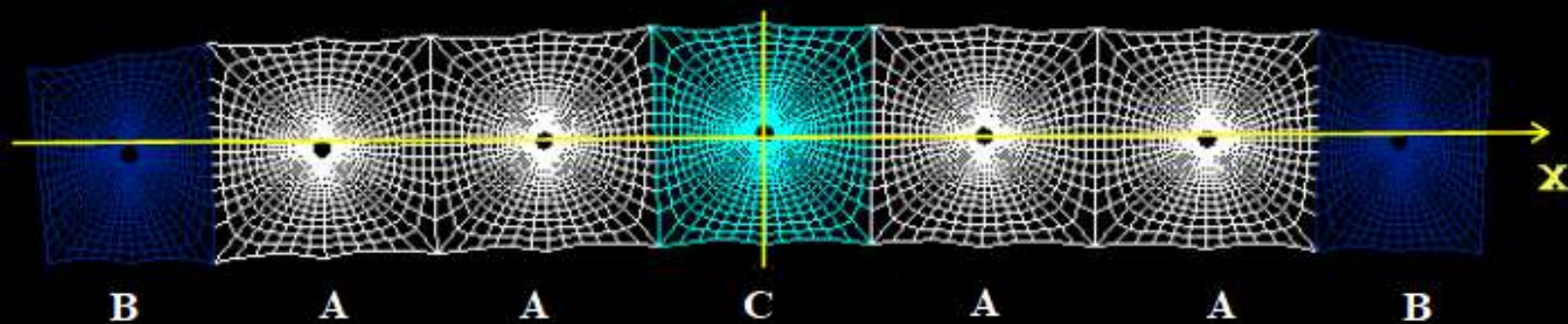




Goiânia's Open Market (2006)



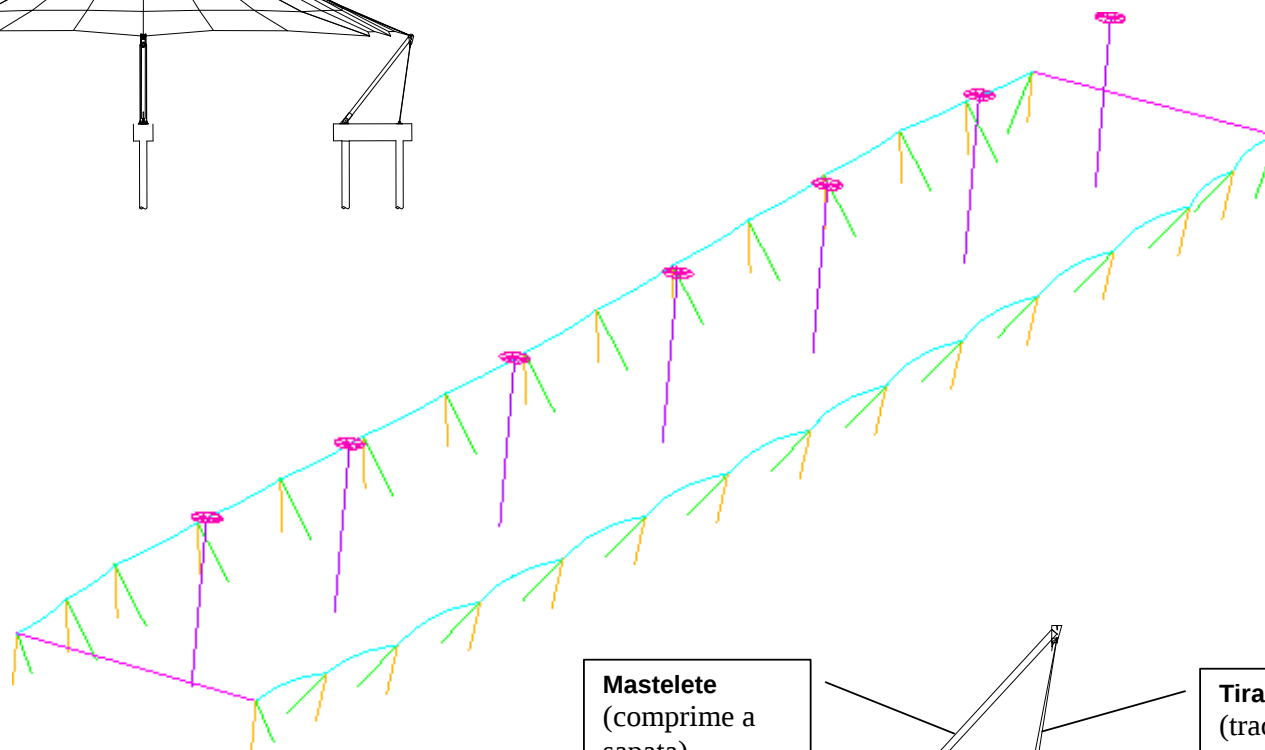
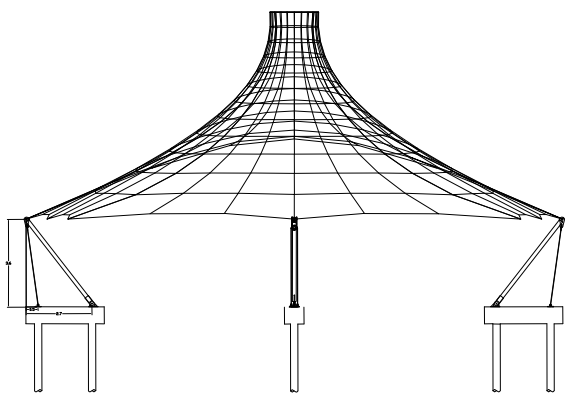






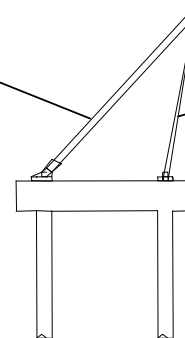


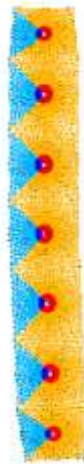
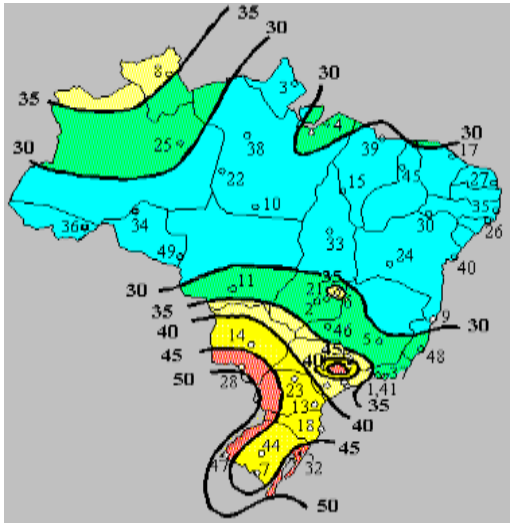




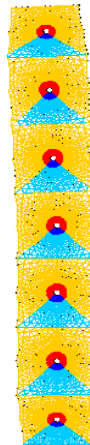
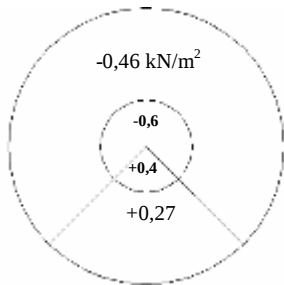
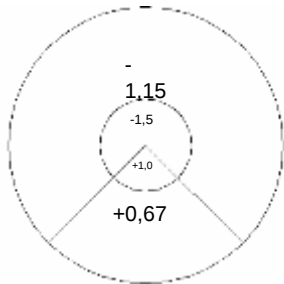
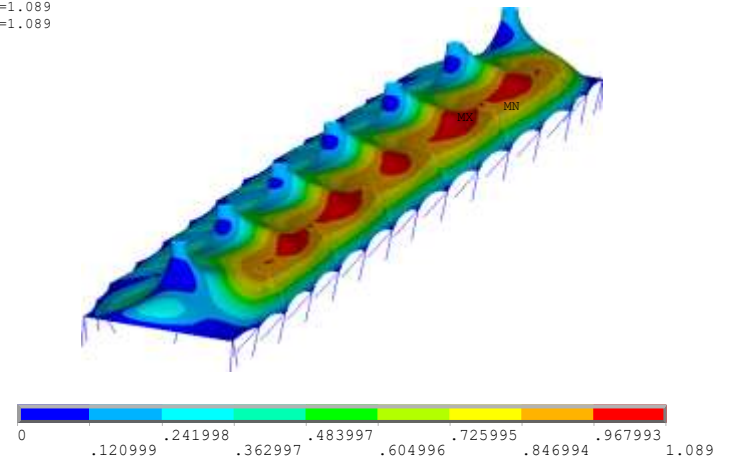
Mastelete
(comprime a
sapata)

Tirante
(traciona a
sapata)

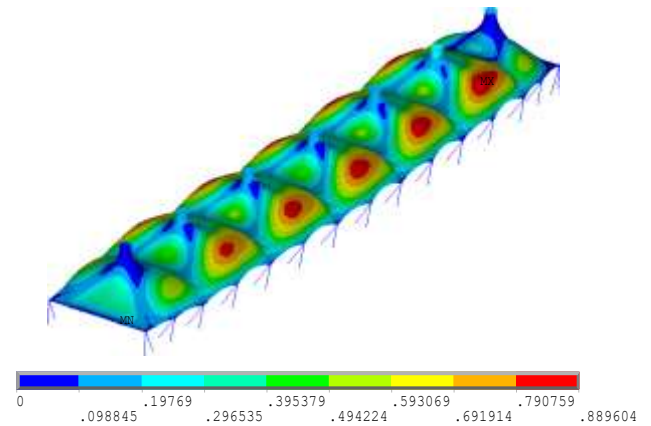




DMX =1.089
SMX =1.089



DMX =.889604
SMX =.889604







"Feira da Cidade de Ananindeua, PA (2006)
Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento



"Feira da Cidade de Ananindeua, PA (2006)
Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento

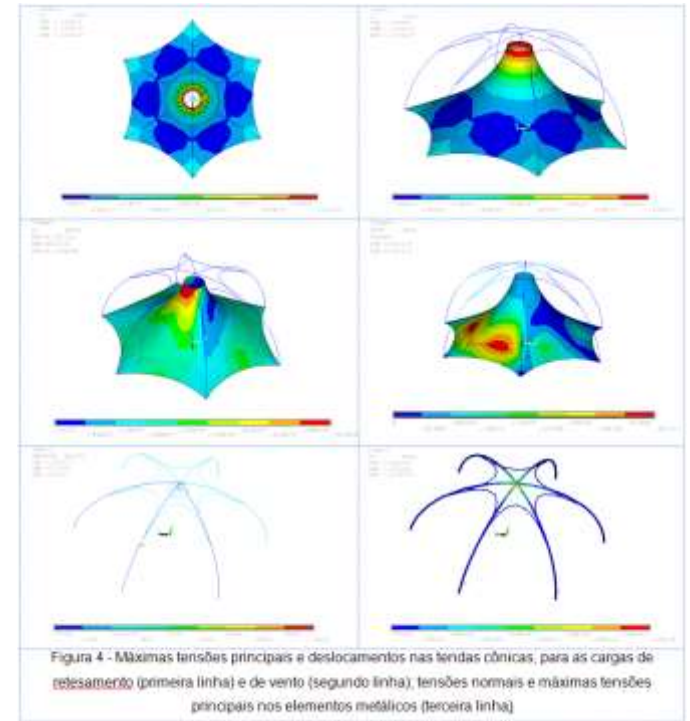


Figura 4 - Máximas tensões principais e deslocamentos nas tendas cônicas, para as cargas de relesamento (primeira linha) e de vento (segundo linha), tensões normais e máximas tensões principais nos elementos metálicos (terceira linha)

"Feira da Cidade de Ananindeua, PA (2006)
Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento

CENPES II – Rio de Janeiro, 2010

Archs. Ziegbert Zenettini, Wagner Garcia





CENPES II

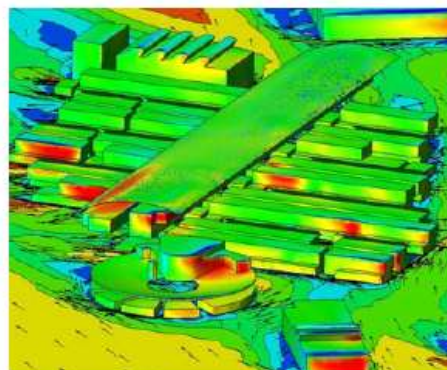
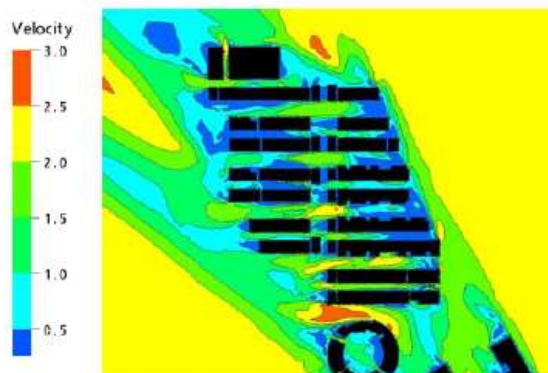
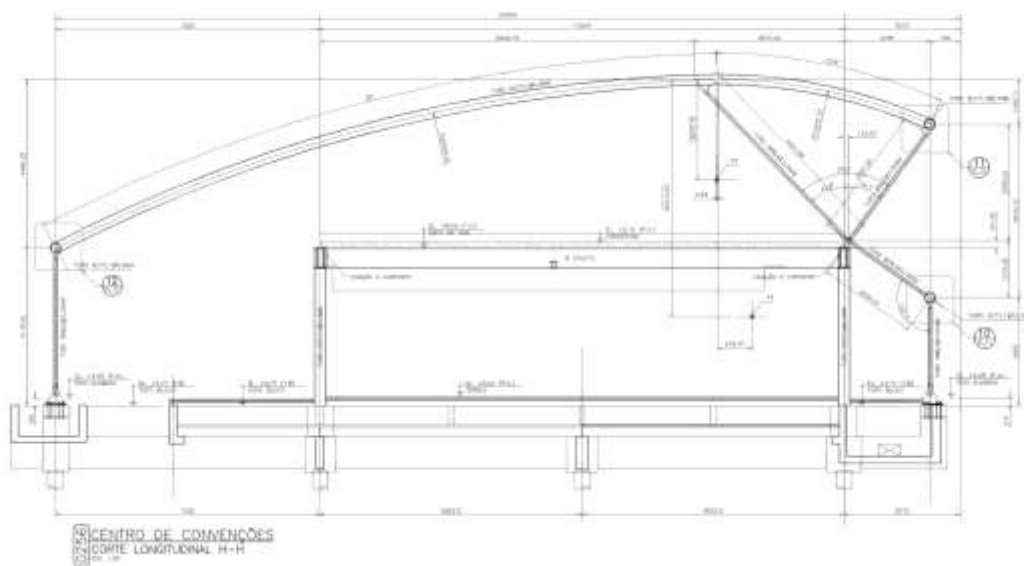
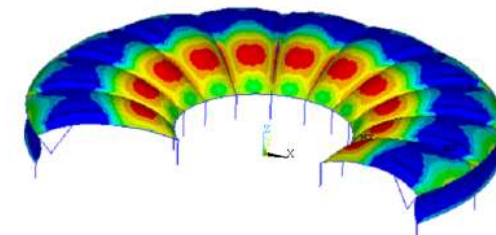
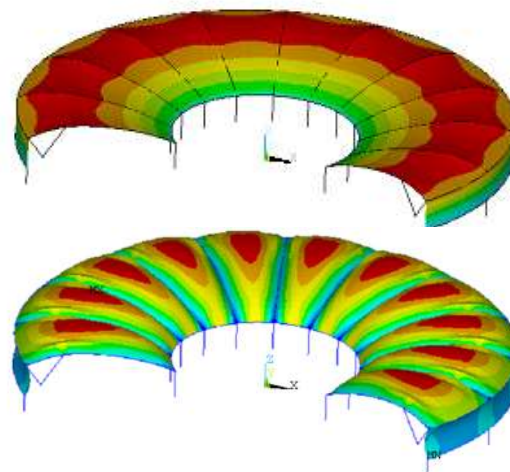


Figura 4 – À esquerda, distribuição da velocidade do vento no nível do pedestre, a 1,5m. Observar escala de velocidades de 0m/s a 3m/s. À direita, distribuição de pressões de vento sobre as envoltórias.





Membranes on top of 'Morro da Urca', Rio de Janeiro, 2014

Designers:

(1) Nelson Fielder

(2) Pedro Marcelo Pain de Santana



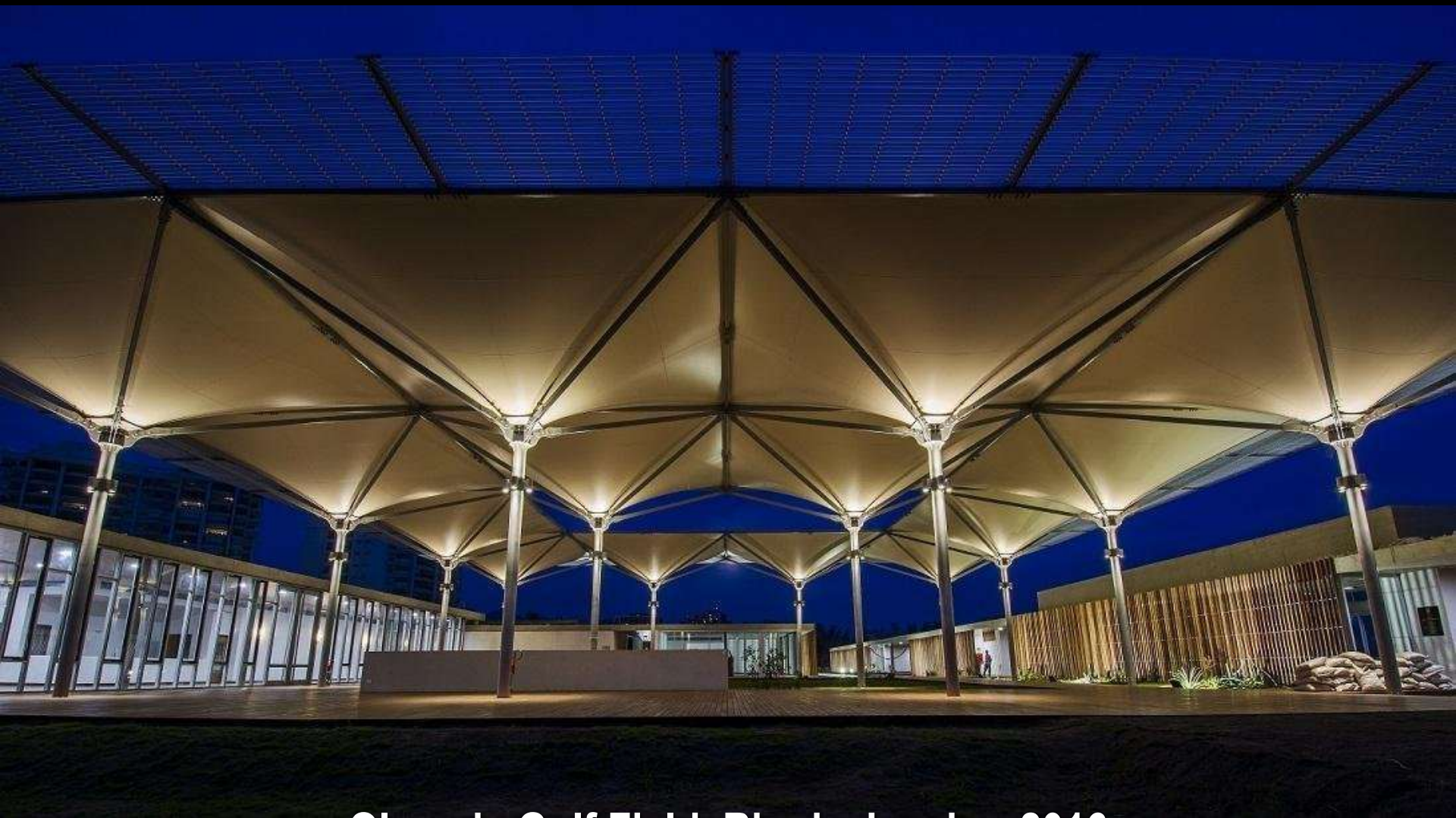




Olympic Golf Field, Rio de Janeiro, 2016



Olympic Golf Field, Rio de Janeiro, 2016

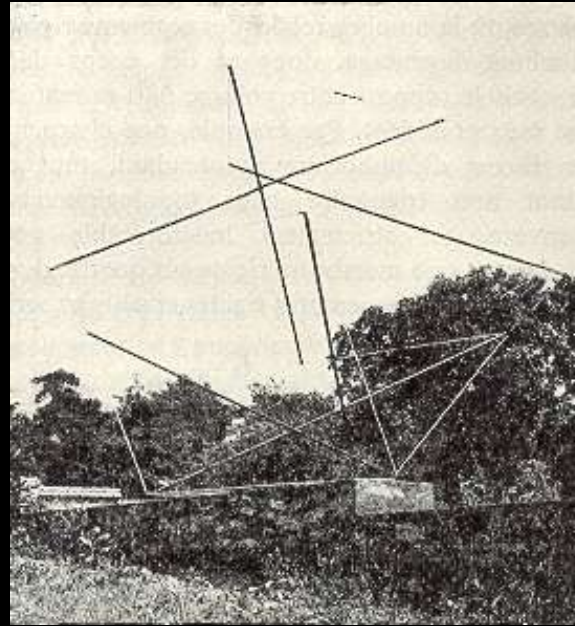


Olympic Golf Field, Rio de Janeiro, 2016

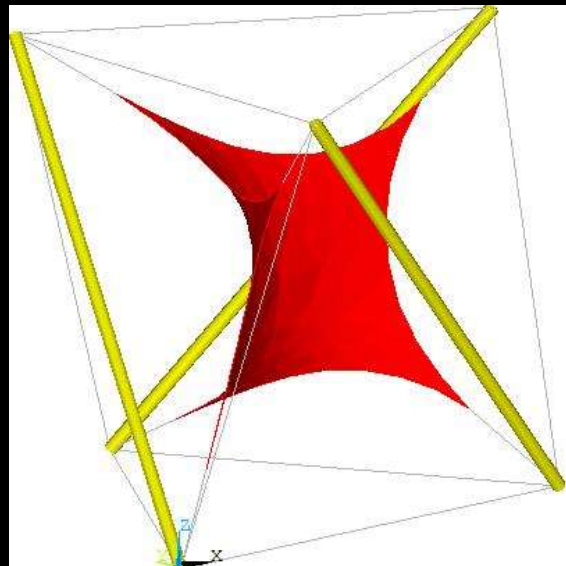
Tensegrities



**Needle Tower,
K. Snelson, 1948**



**The Monument to
the Futile Form,
D. Emmerich, 1966**

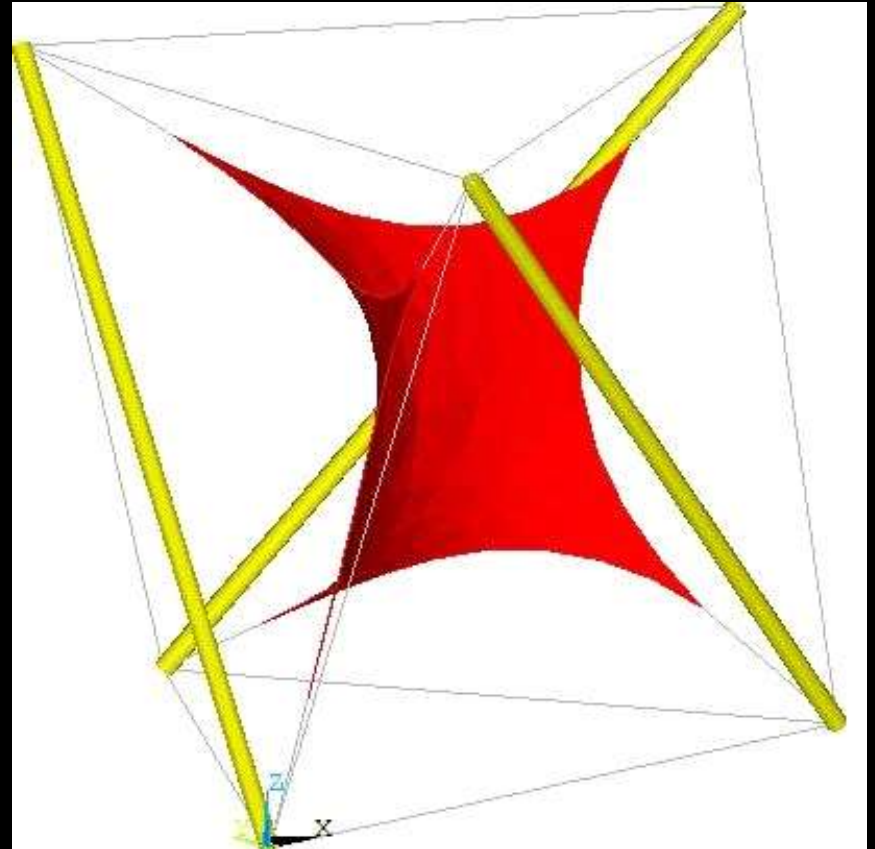


**The Monument to the
Futile Form II
Titotto, Deifeld, Pauletti,
2003**

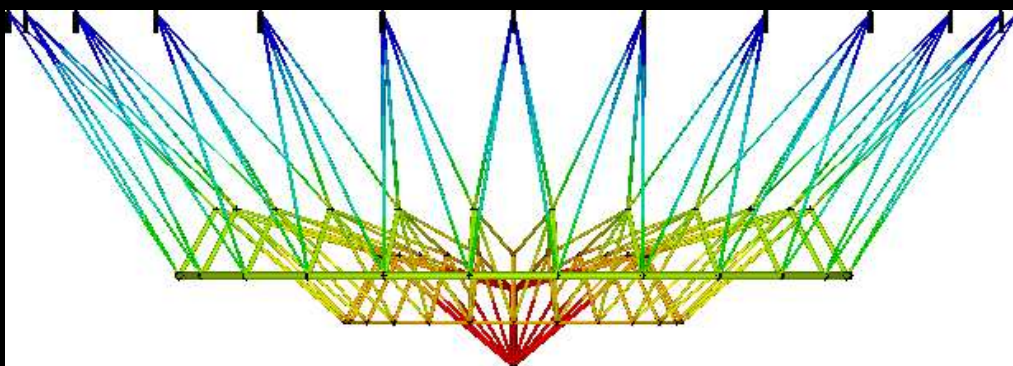
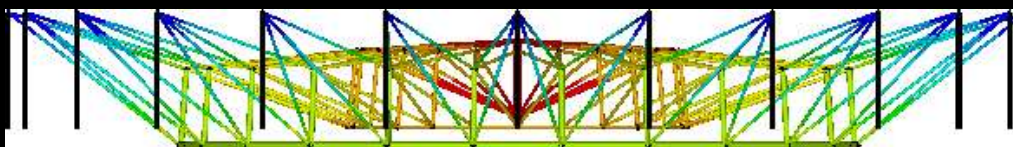
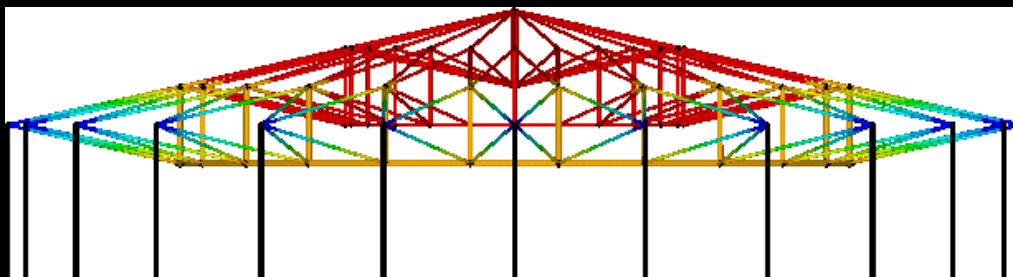
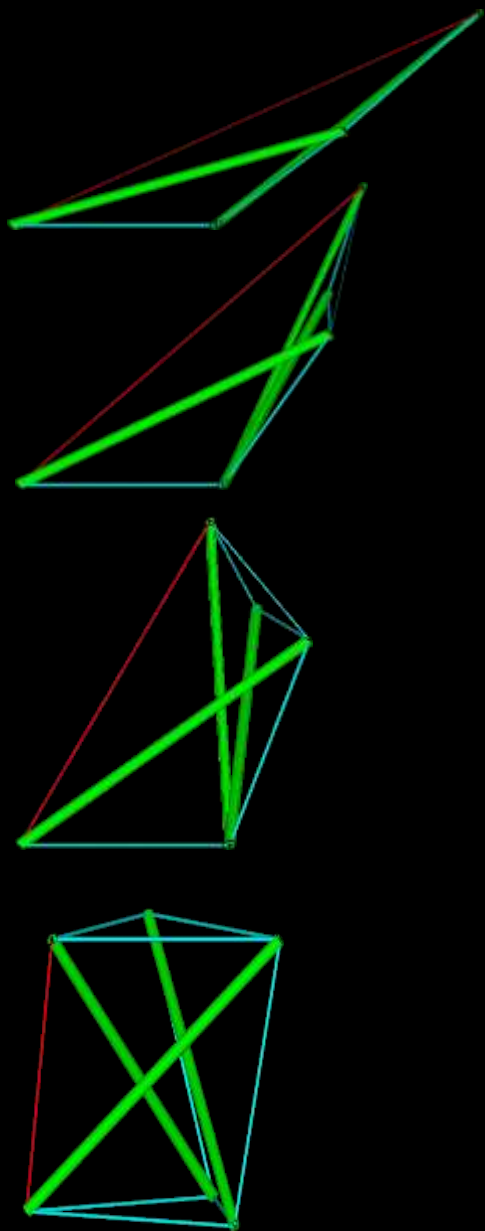


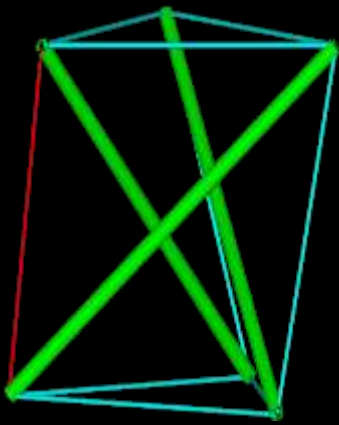


Monument to the Futile Form II (2003)



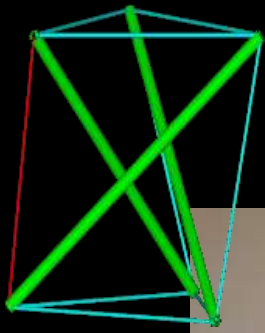




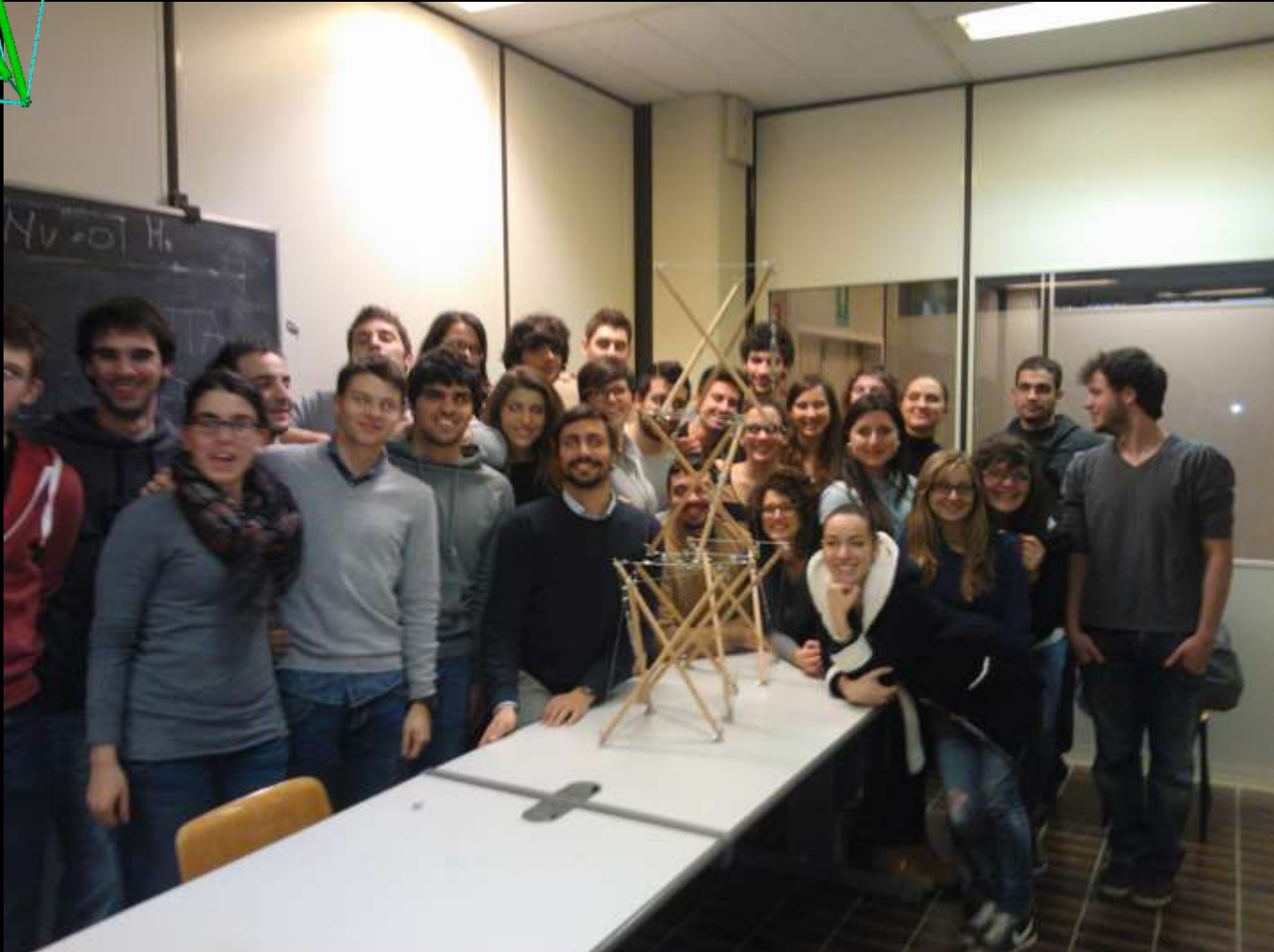


3 days workshop at Università delle Marche (ancona) (2013)

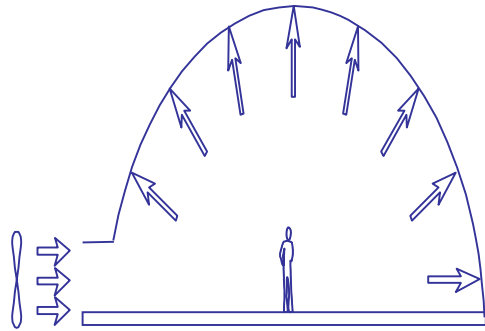




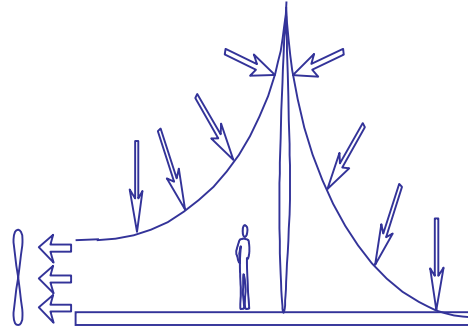
3 days workshop at Università delle Marche (Ancona) (2013)



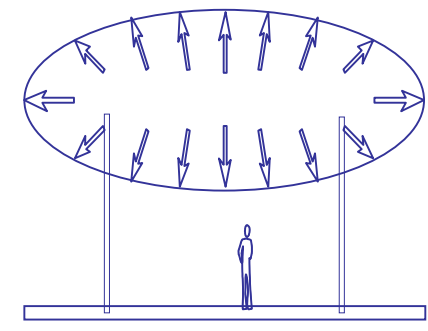
Pneumatic Structures



(a) Insufflated;



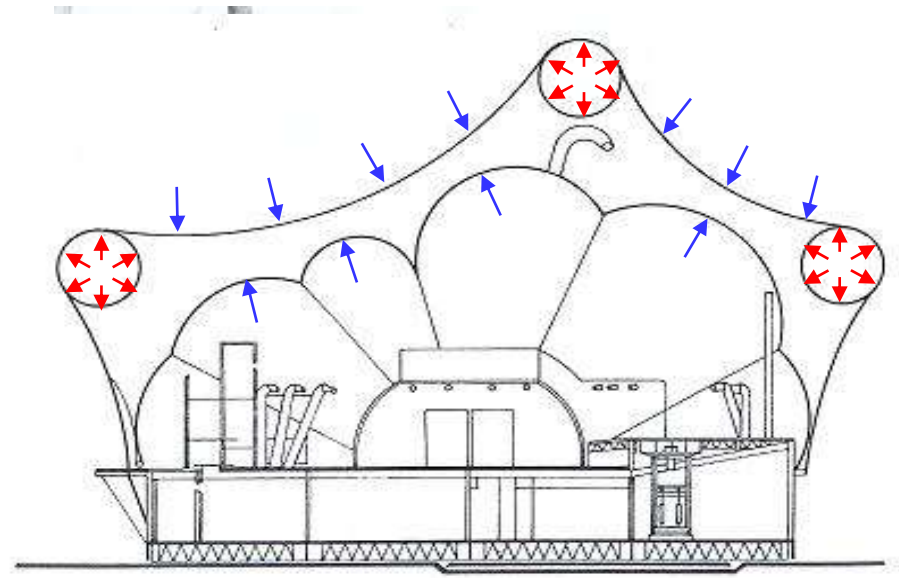
(b) Aspirated;



(c) Inflated



Tokyo "Big-Egg" Dome (1988)



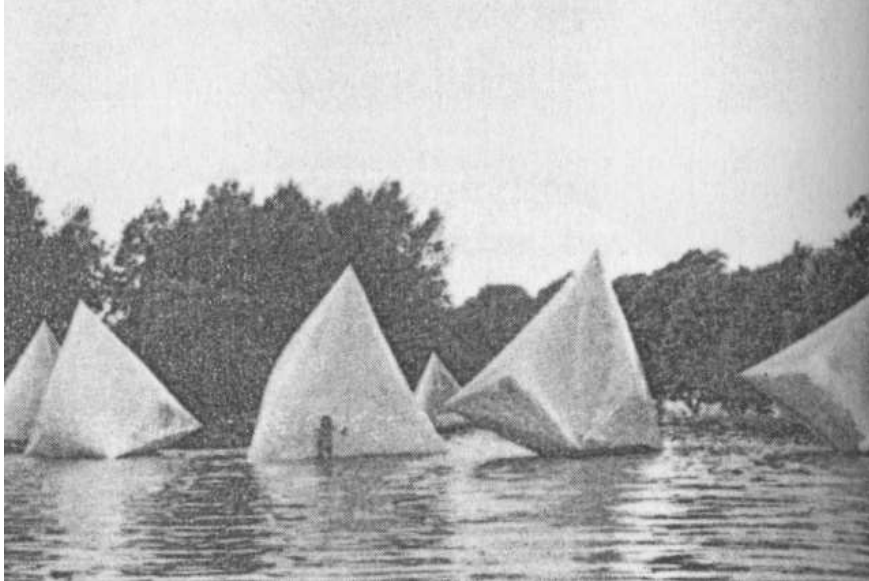
Floating Pavilion (Osaka, 1970)



Inflated tetrahedron 'walking machine'

Eventstructure Research Group, 1968.

*0.5 mm thick transparent or translucent PVC foils;
watertight zip fastened entrances.*





*La Balulle -
Gilles Ebersolt, France
(1973 – 1985)*

Zorb:

Dwane van der Sluis & Andrew Akers

New Zealand





Icosahedron

Faces: 20

Edges: 30

Vertices: 12



**truncated
icosahedron**

Faces: 32

Edges: 90

Vertices: 60



Dodecahedron

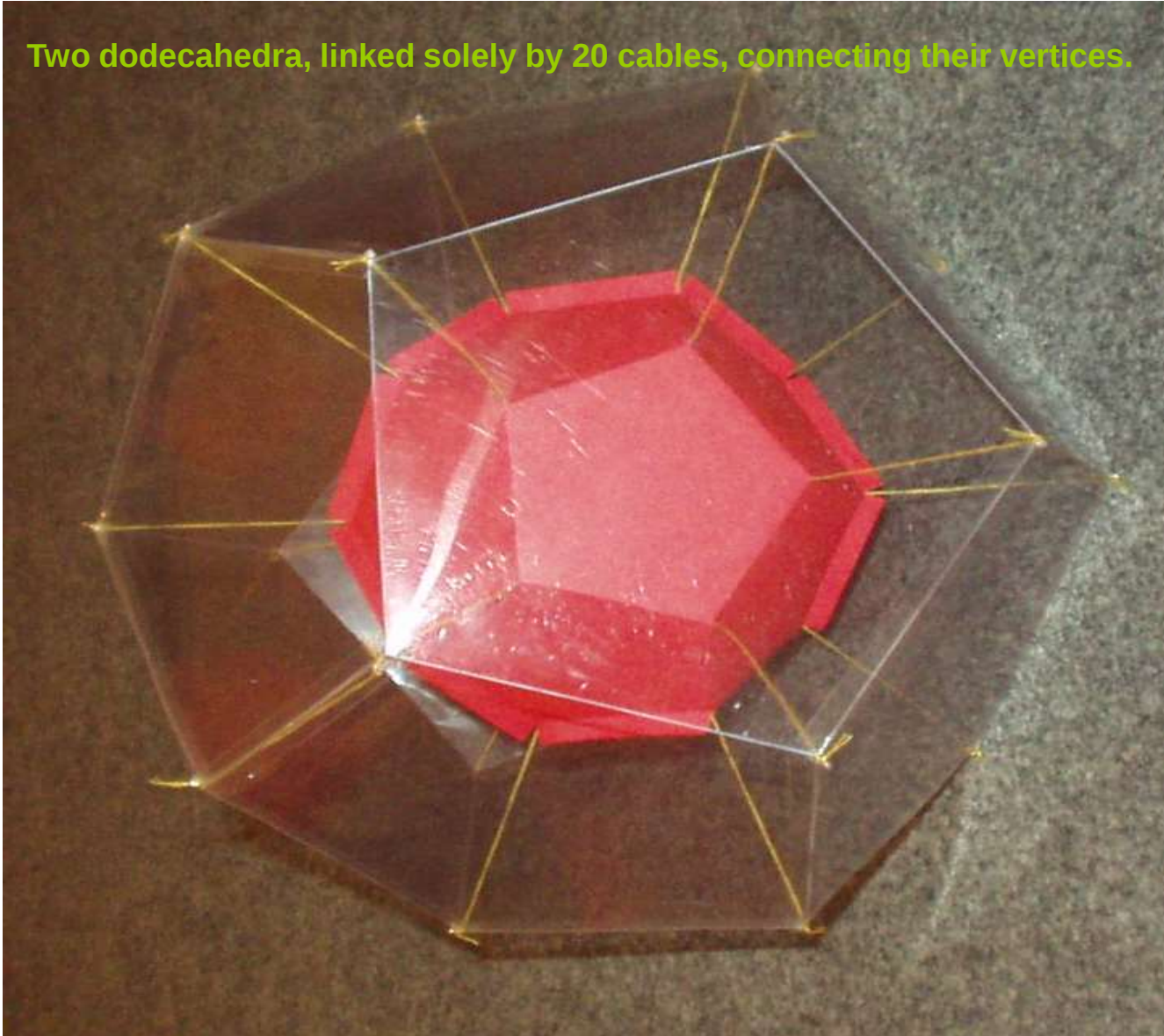
Faces: 12

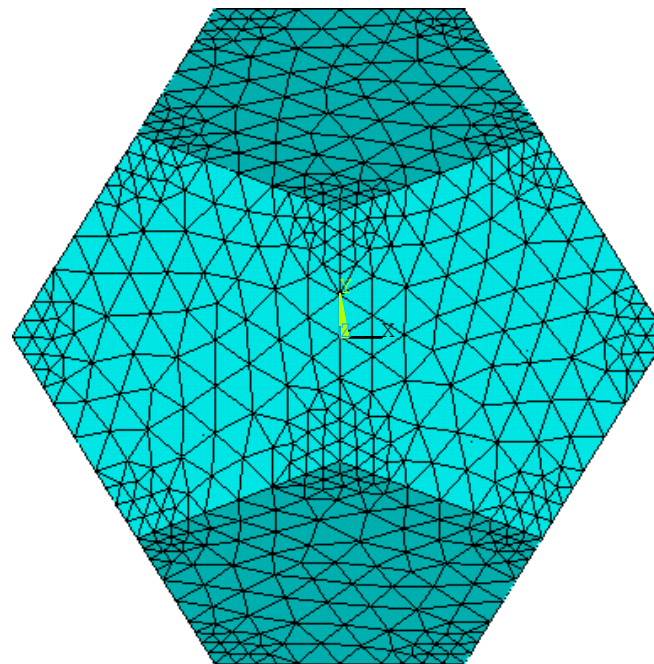
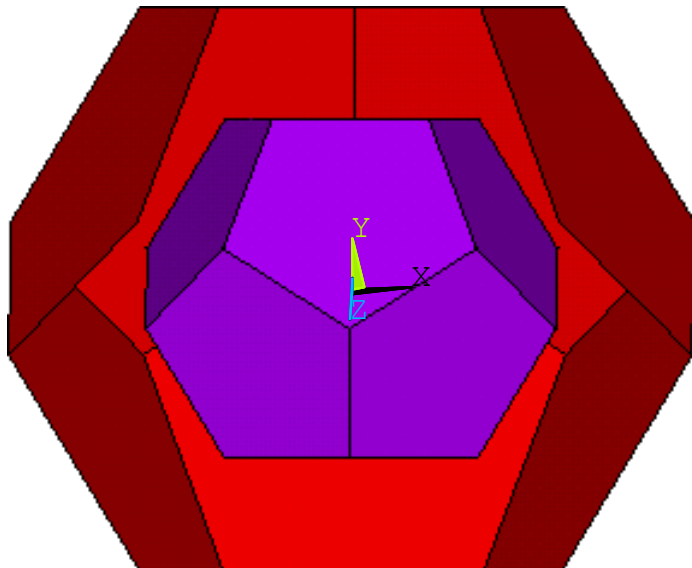
Edges: 30

Vertices: 20

The “Dodecoid”

Two dodecahedra, linked solely by 20 cables, connecting their vertices.

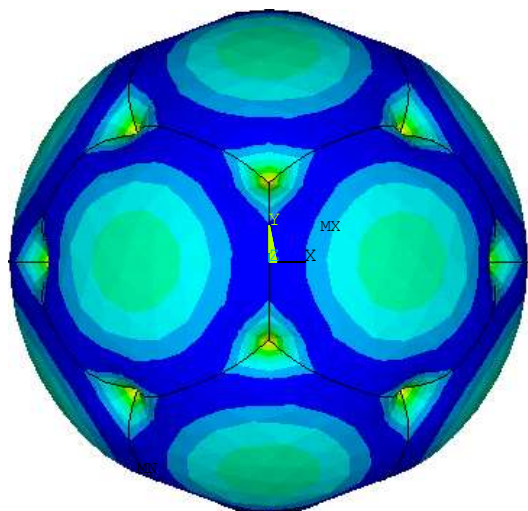




```

---
TIME=2
USUM      (AVG)
RSYS=0
DMX =.353357
SMN =.017586
SMX =.353357

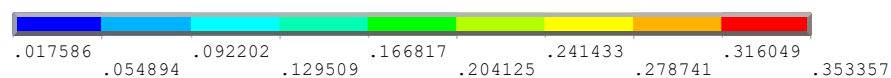
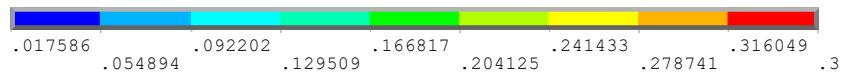
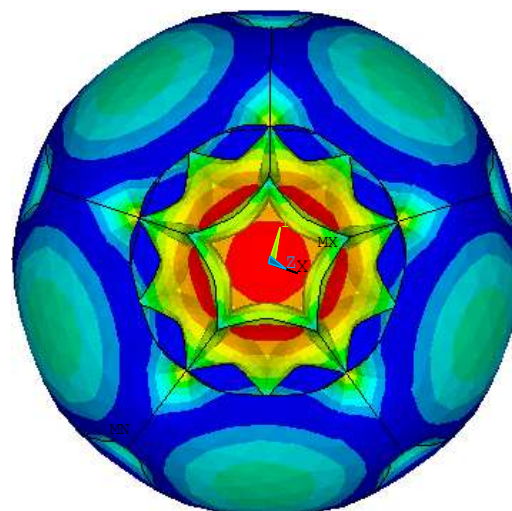
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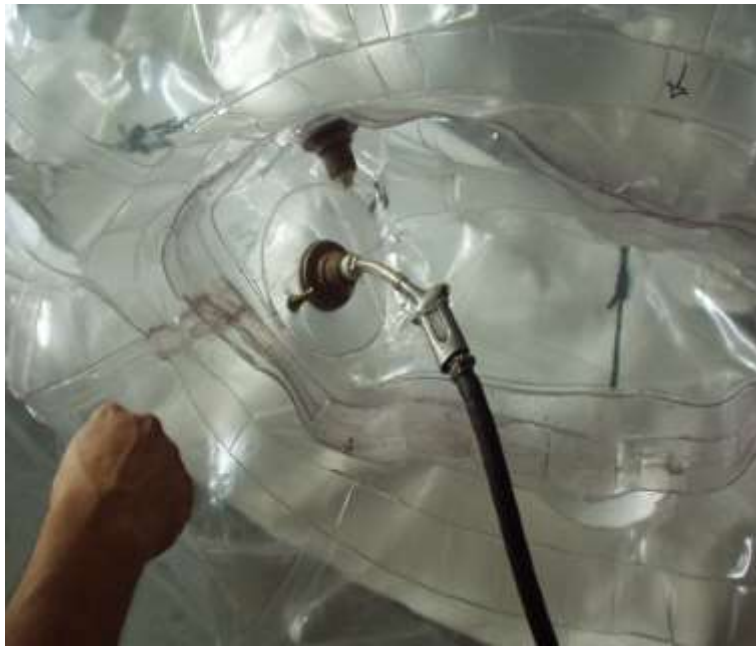
TIME=2
USUM      (AVG)
RSYS=0
DMX =.353357
SMN =.017586
SMX =.353357

```





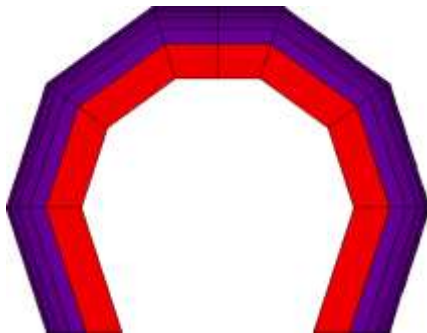
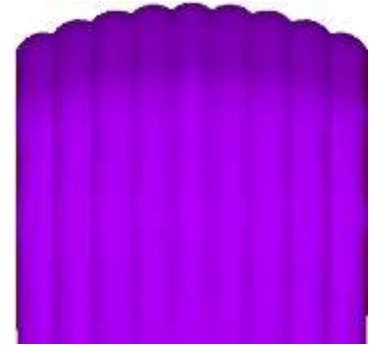
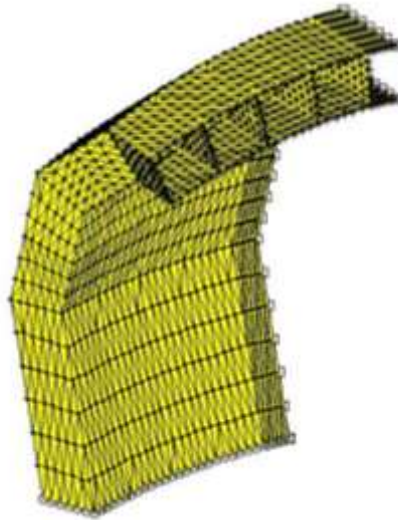
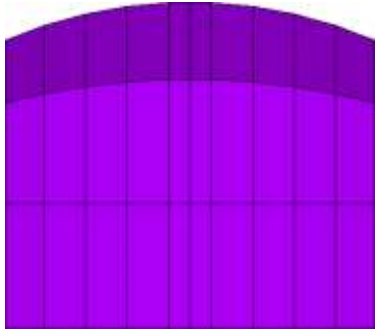




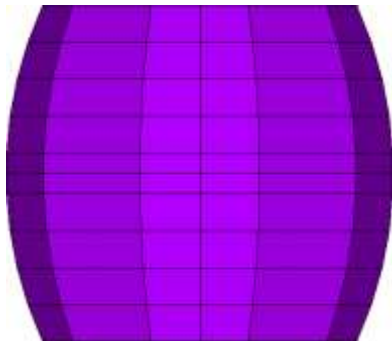
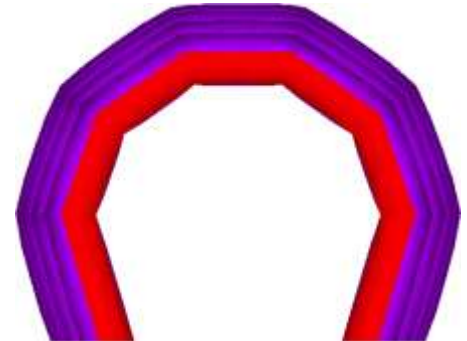
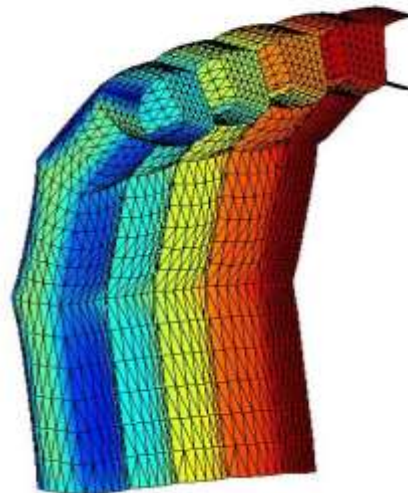


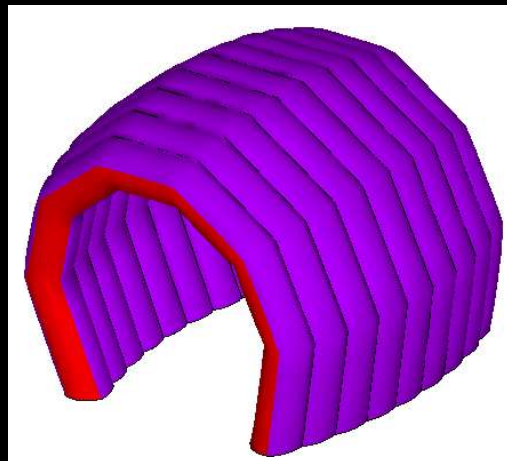
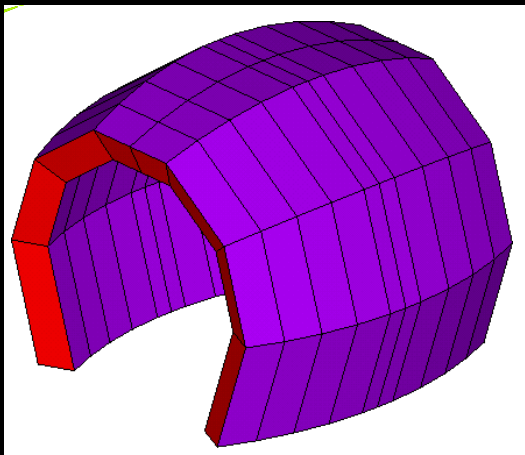


A pneumatic dome (2005)



Deslocamentos UY : min -0.11962 max 0





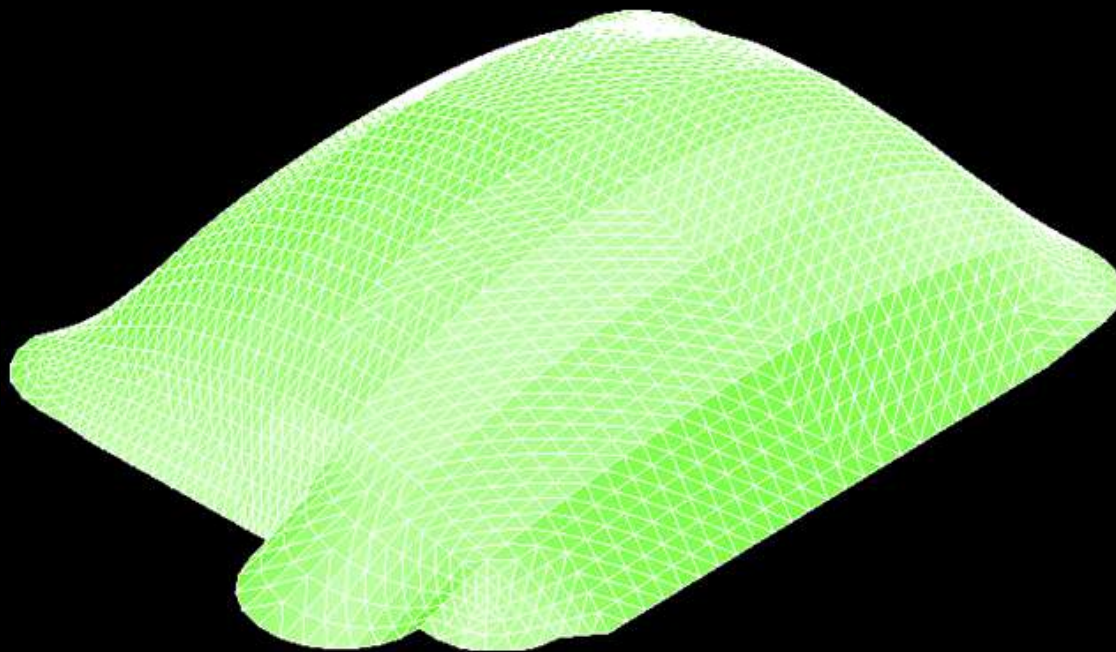
Sliding Cables and Wrinkling



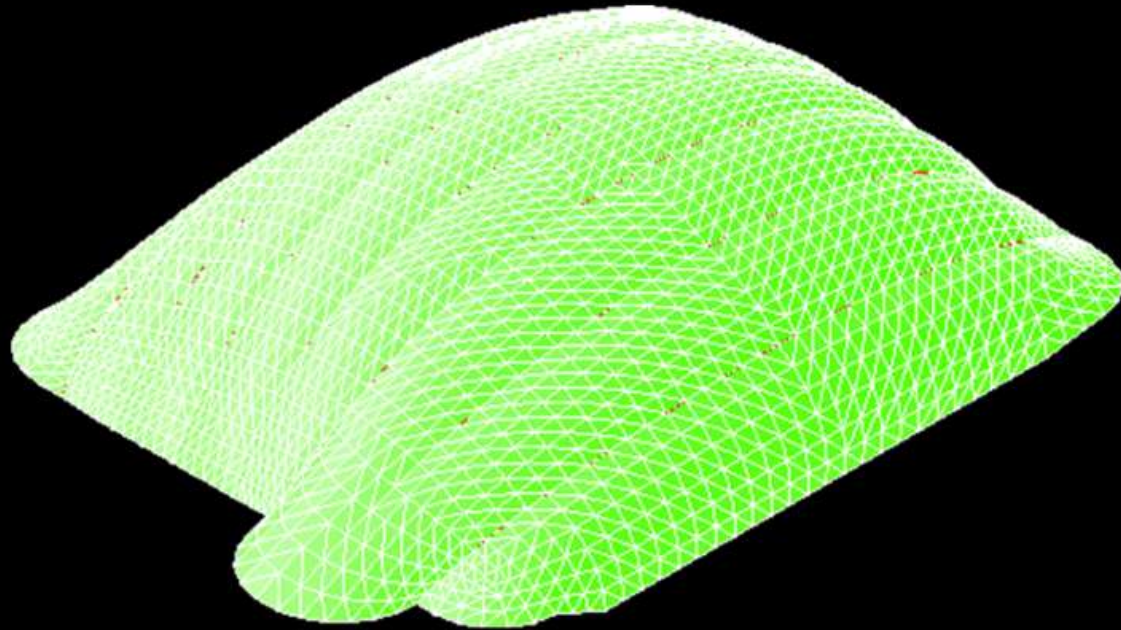
Pneumatic envelope for 'Angra III' ground preparation

(September 2009)



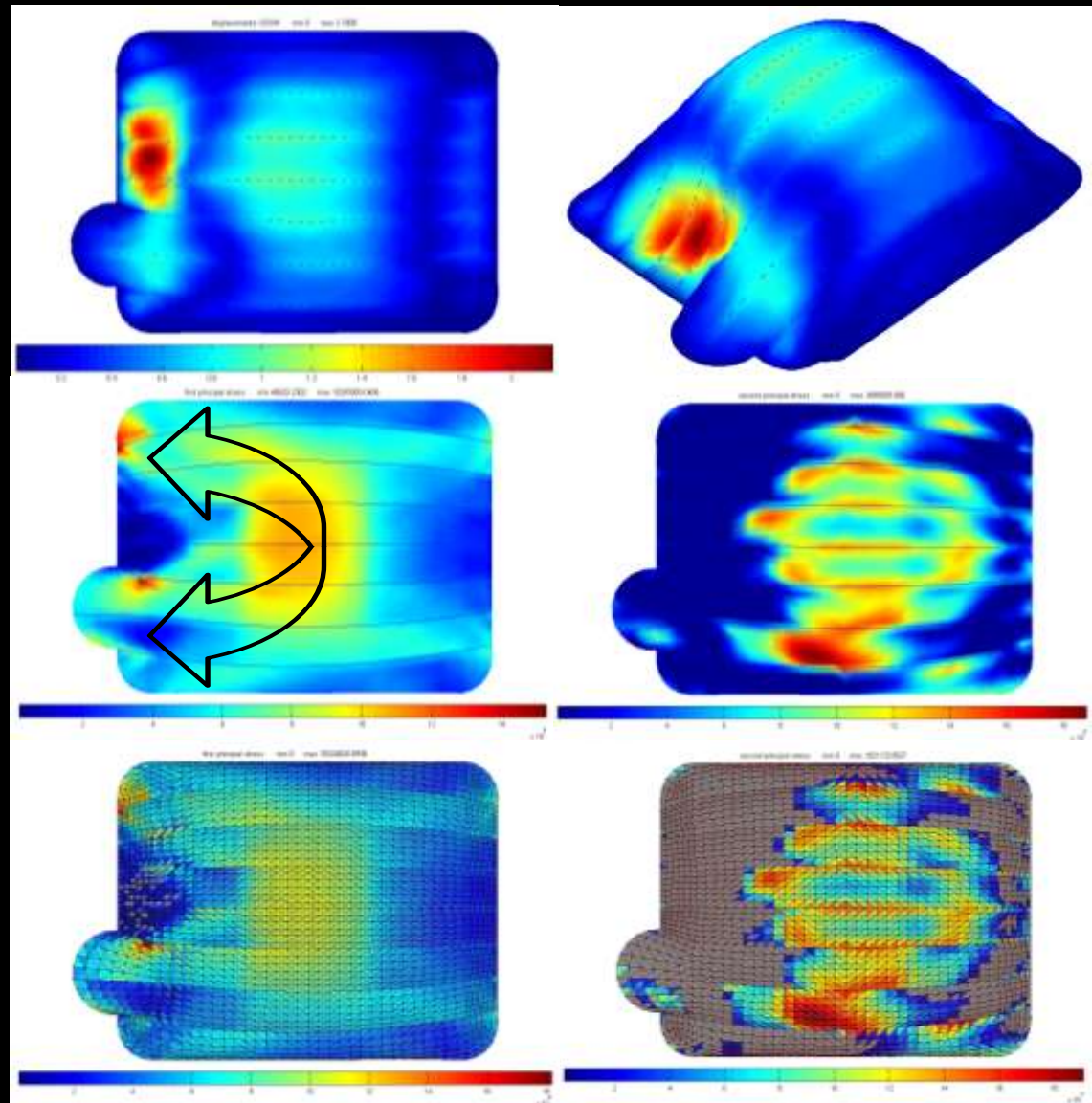
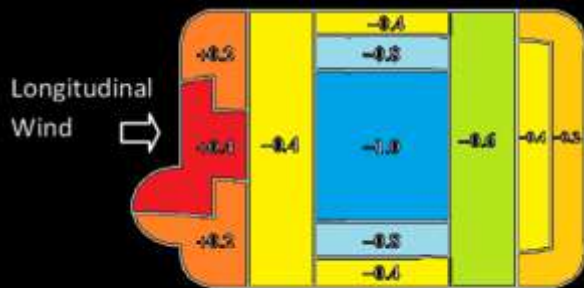


Initial mesh modeled in SATS



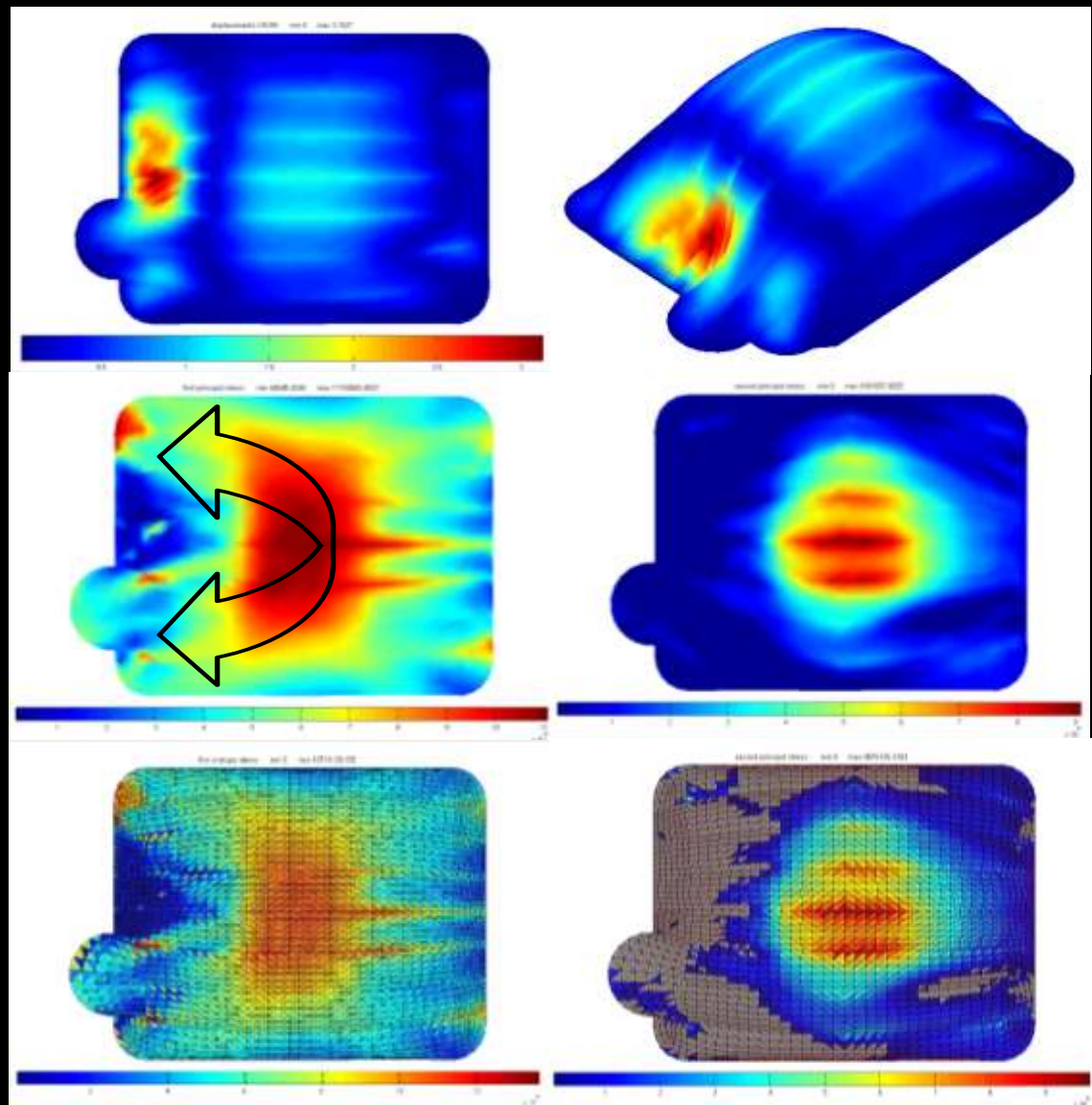
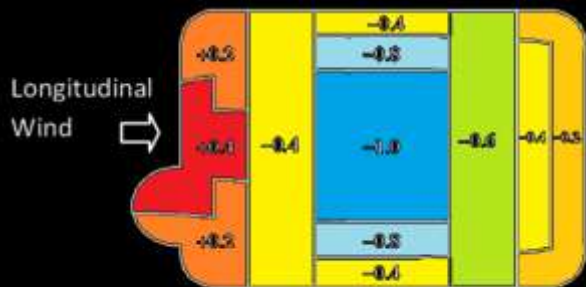
equilibrium geometry under internal pressure

Longitudinal wind,
adherent cables



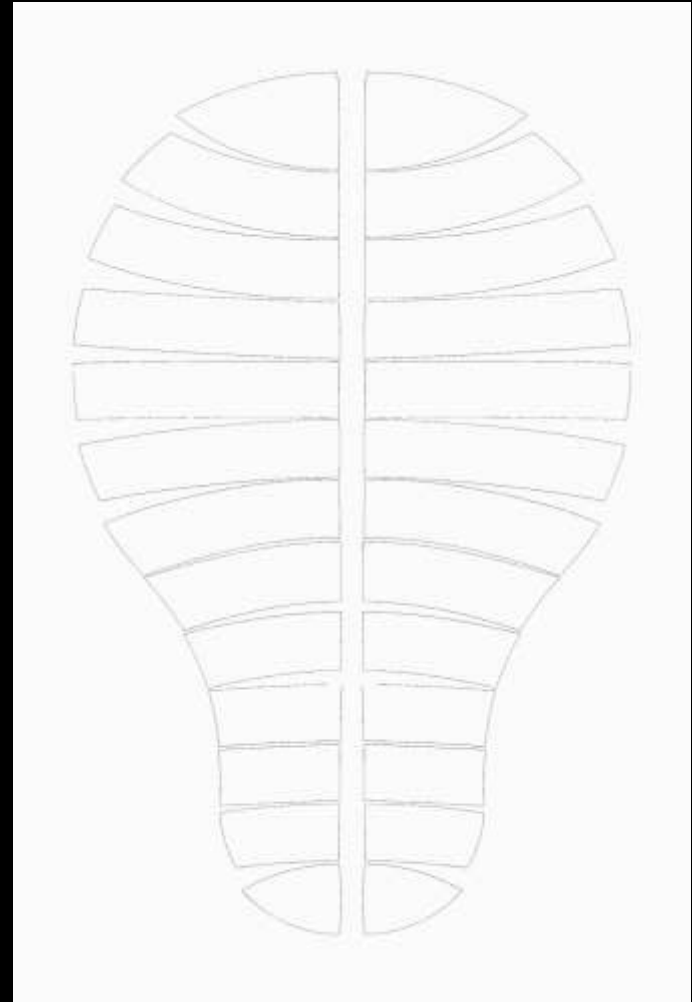
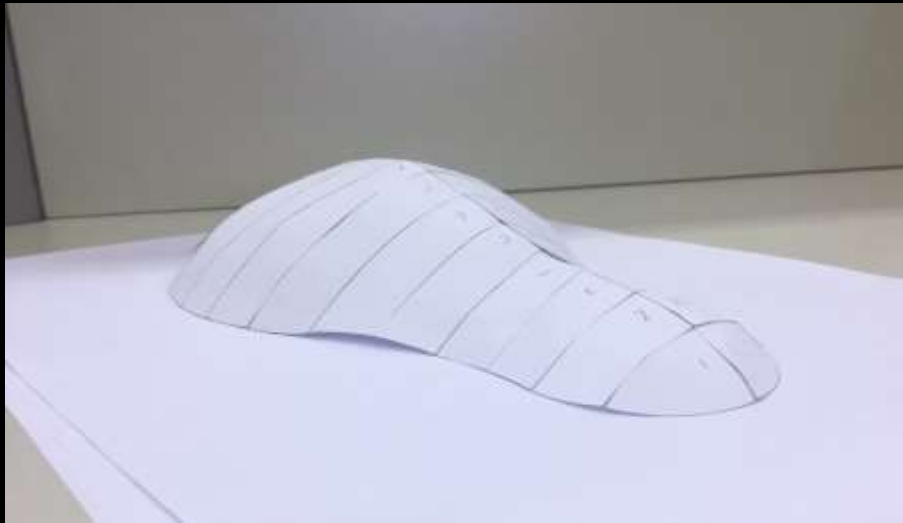
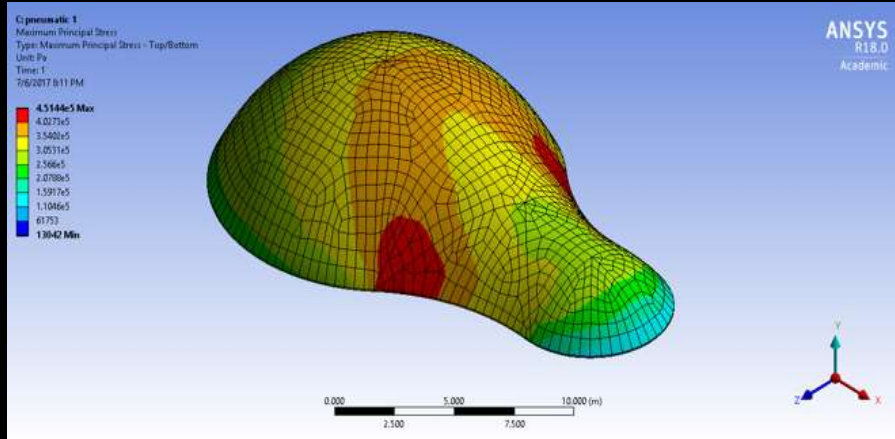
(a) field of displacement norms; (b) *idem*, isometric view; (c) stress field; (d) stress field.

Longitudinal wind,
sliding cables



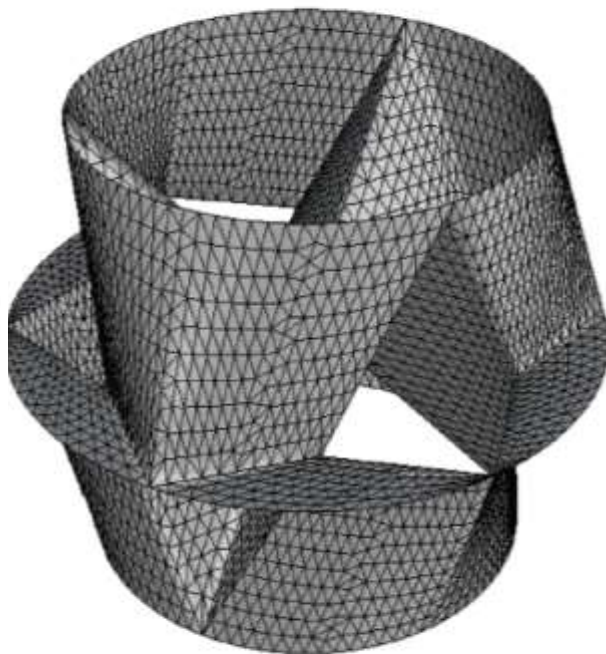
(a) field of displacement norms; (b) *idem*, isometric view; (c) stress field; (d) stress field.

Pneumatic Formworks:

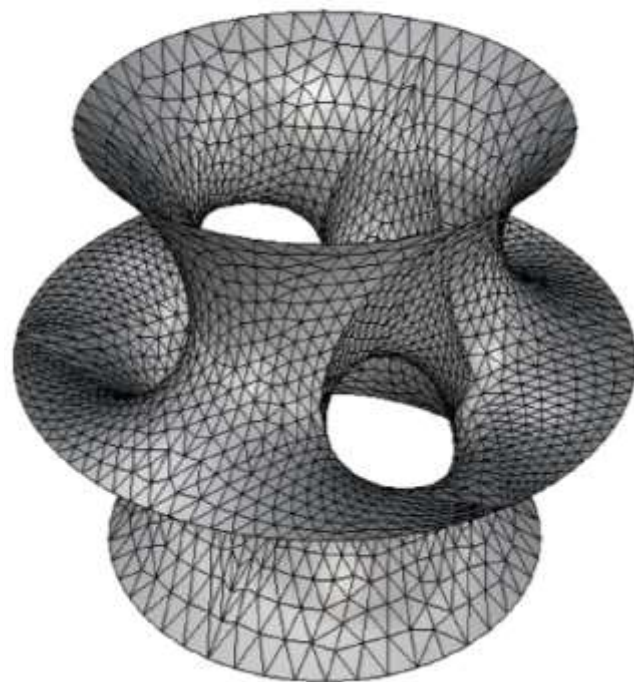




A Minimal Surface Membrane Sculpture (Princeton, 2017)



INITIAL MESH



FINAL MESH

EXPLORED SOLUTION METHODS

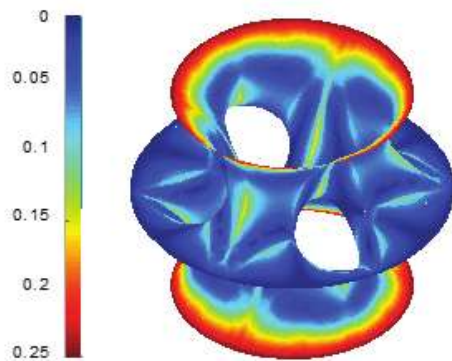
1. Direct Area Minimization

1.2. Dynamic Relaxation Method:

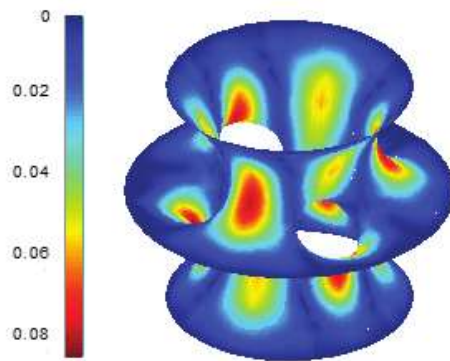
Time-integrate

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{p}(\mathbf{u}) = \mathbf{0}$$

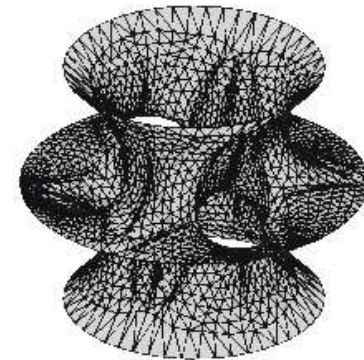
$\mathbf{M}, \mathbf{C}$ are arbitrary matrices



DISPLACEMENT FIELD (iter 0-500)
Maximum Displacement: 0.25



DISPLACEMENT FIELD (iter 500-1,000)
Maximum Displacement: 0.0845



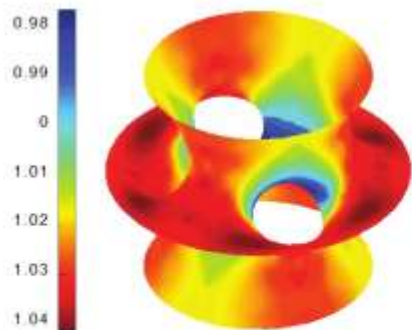
FINAL MESH

Results for Direct Area Minimization solved by
Dynamic Relaxation Method

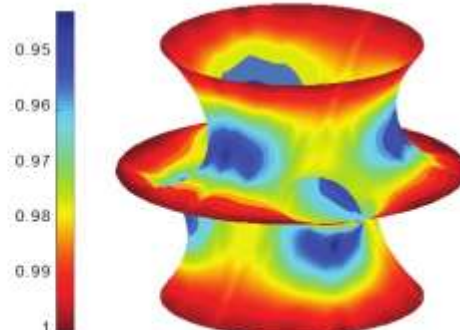
EXPLORED SOLUTION METHODS

2. Soap Film's Analogy : search for a shape associated with a self-equilibrated homogeneous and isotropic stress field.

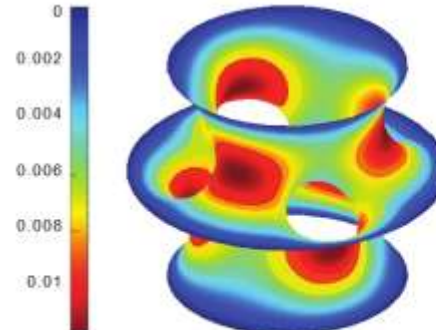
2.1. Newton Method Iterate $\mathbf{u}_{i+1} = \mathbf{u}_i - \mathbf{K}_i^{-1} \mathbf{p}_i$ where $\mathbf{K} = \frac{\partial \mathbf{p}}{\partial \mathbf{u}}$ is the tangent stiffness matrix



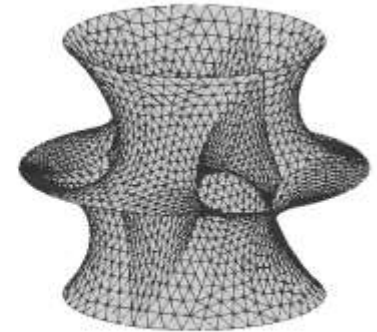
FIRST PRINCIPLE STRESS
Min: 0.976 Max: 1.042



SECOND PRINCIPLE STRESS
Min: 0.942 Max: 1.000



DISPLACEMENT FIELD
Maximum Displacement: 0.0116



FINAL MESH

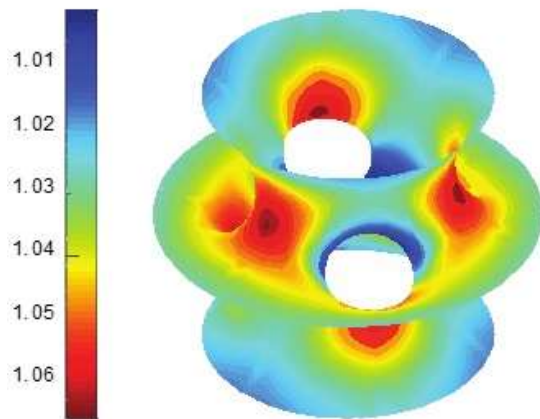
Results for Soap Film Analogy solved by
Newton's Method

EXPLORED SOLUTION METHODS

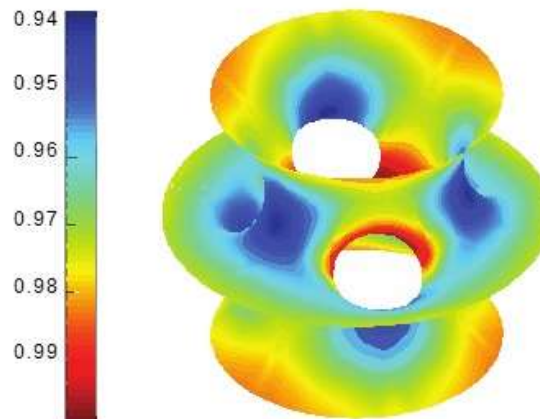
2. Soap Film's Analogy : search for a shape associated with a self-equilibrated homogeneous and isotropic stress field,.

2.2. Natural Force Density Method:

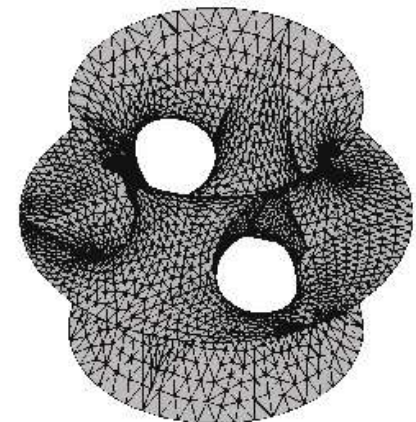
Calculate some natural force densities: $\mathbf{n} = V \mathcal{L}^{-2} \mathbf{T}^{-T} \boldsymbol{\sigma}_0$
from a prescribed homogeneous and isotropic stress field $\boldsymbol{\sigma}_0$
Solve a linear system, and iterate, re-imposing



FIRST PRINCIPLE STRESS
Min: 1.001 Max: 1.066



SECOND PRINCIPLE STRESS
Min: 0.938 Max: 0.999



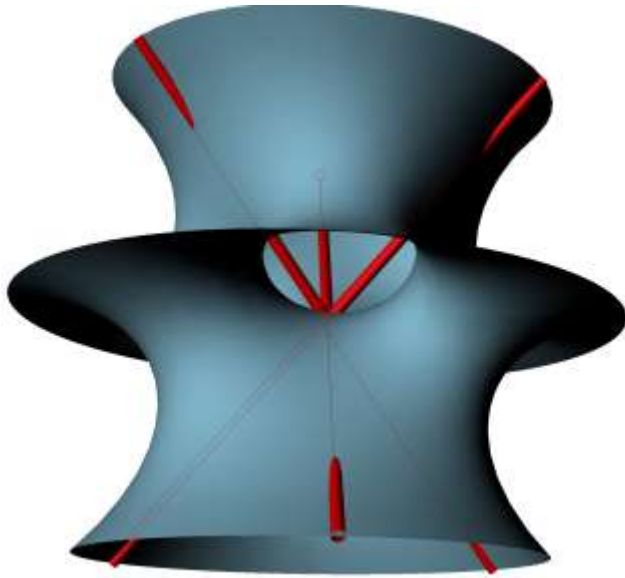
FINAL MESH

Results for Soap Film Analogy solved by
Natural Force Density Method

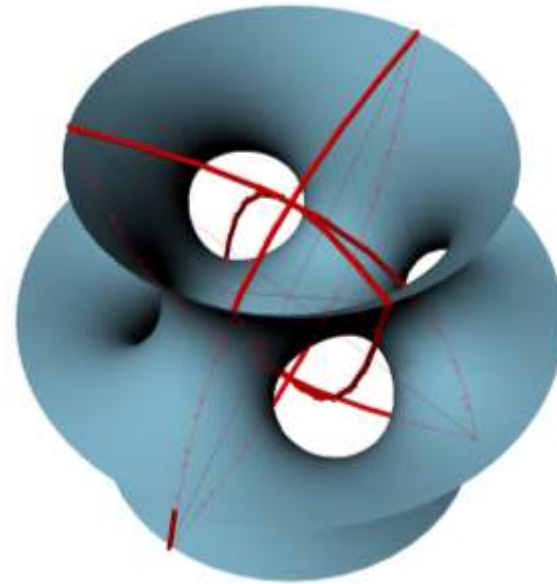
EXPLORED SOLUTION METHODS

Method	Surface Area at Convergence	Iterations
Dynamic Relaxation	8.248 m ²	1000
Newton's Method	8.286 m ²	18
Natural Force Density	8.253 m ²	5

ACTIVE-BENDING SUPPORT PRESTRESSING SYSTEM



Straight bars interfere
with the membrane surface

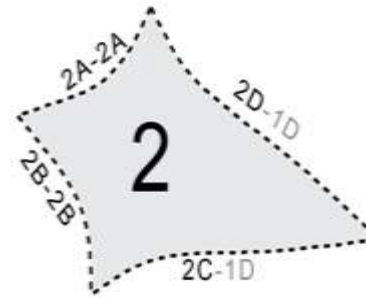
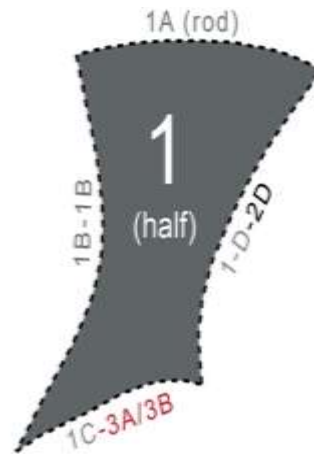


Bent bars can be
accommodated and provide a
convenient activating system

PATTERNING



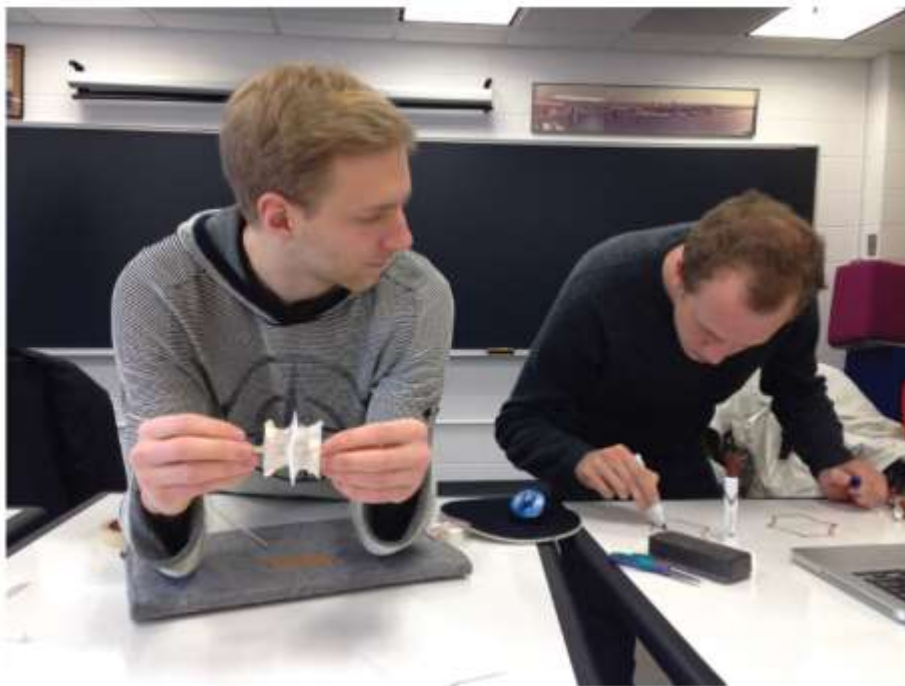
PERSPECTIVE VIEW

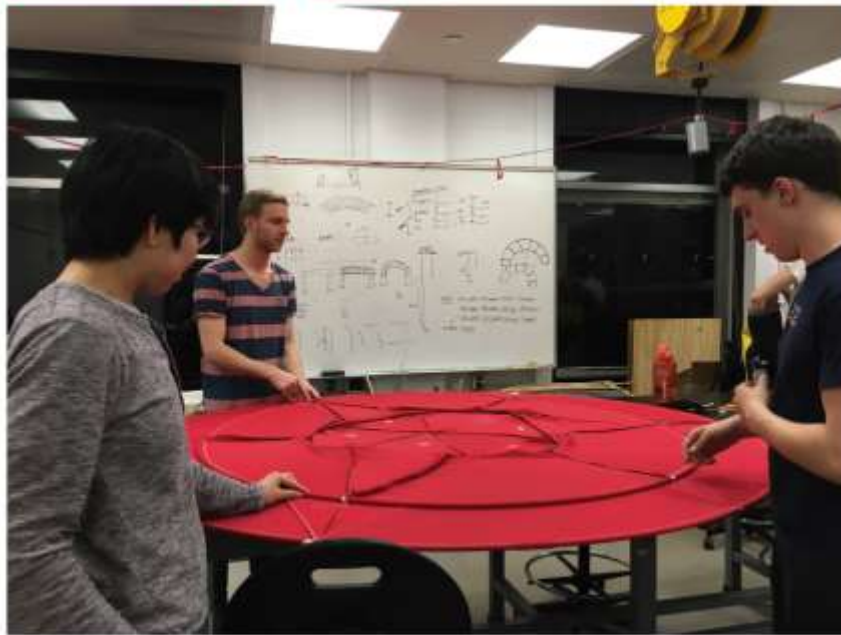
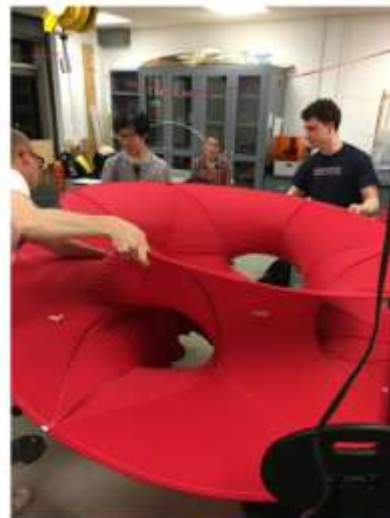


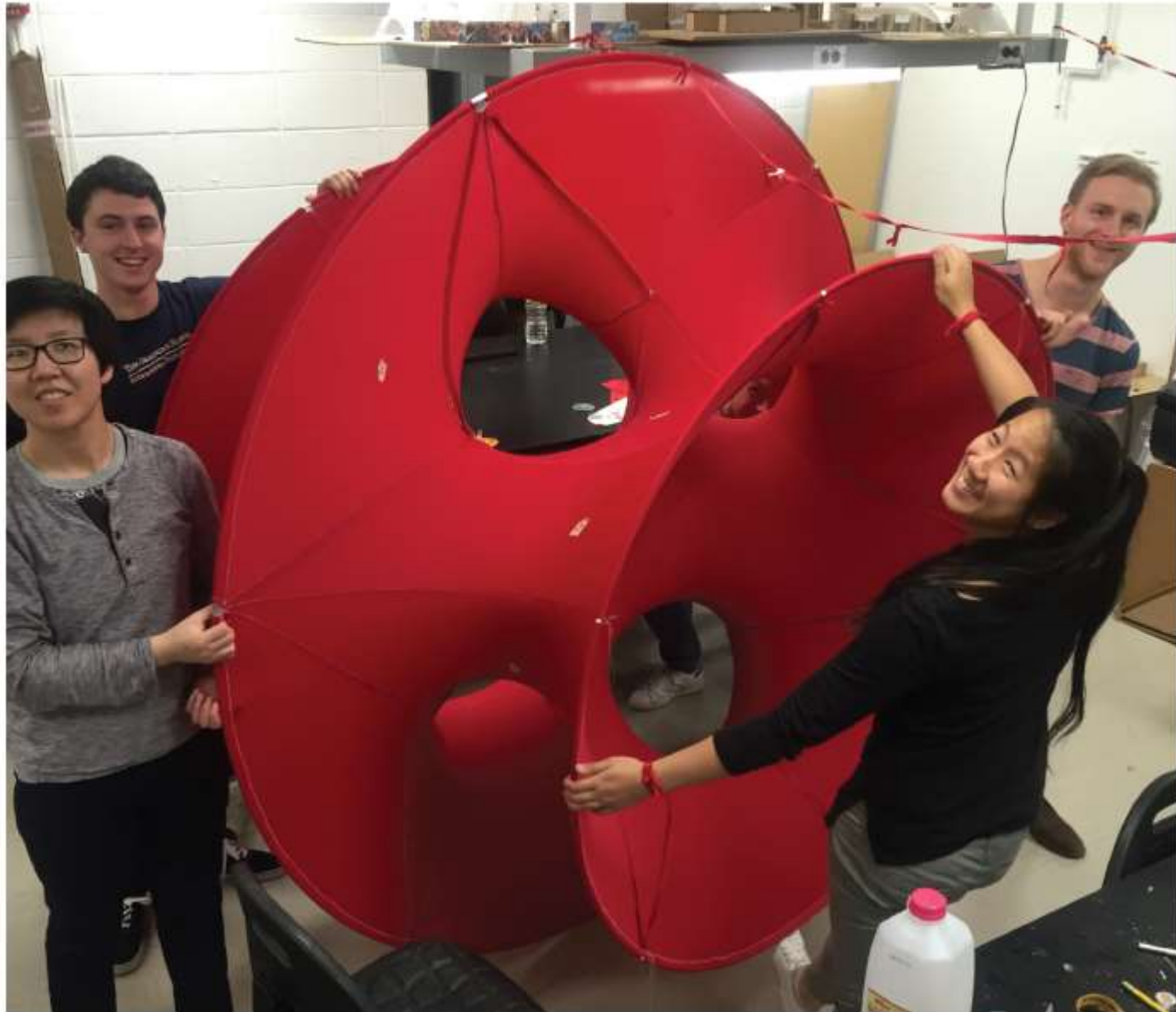
FLATTENED PATTERNS

DOCUMENTATION OF THE FABRICATION PROCESS



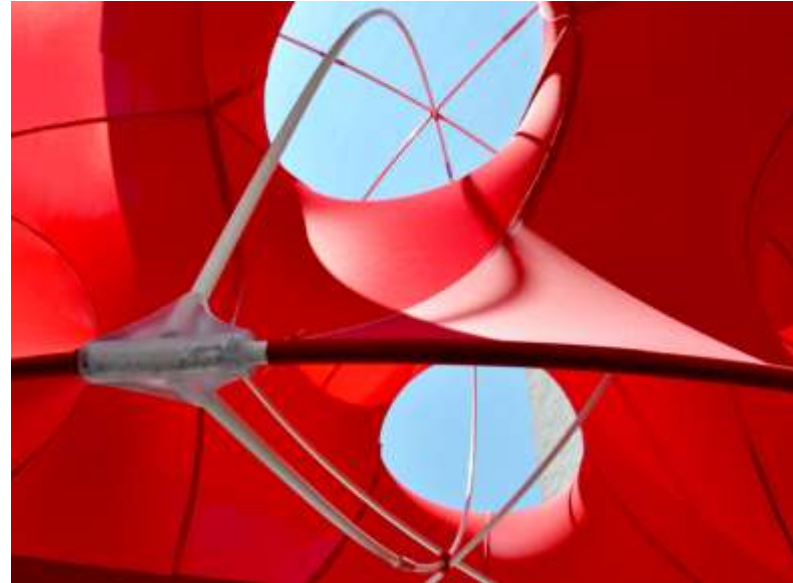
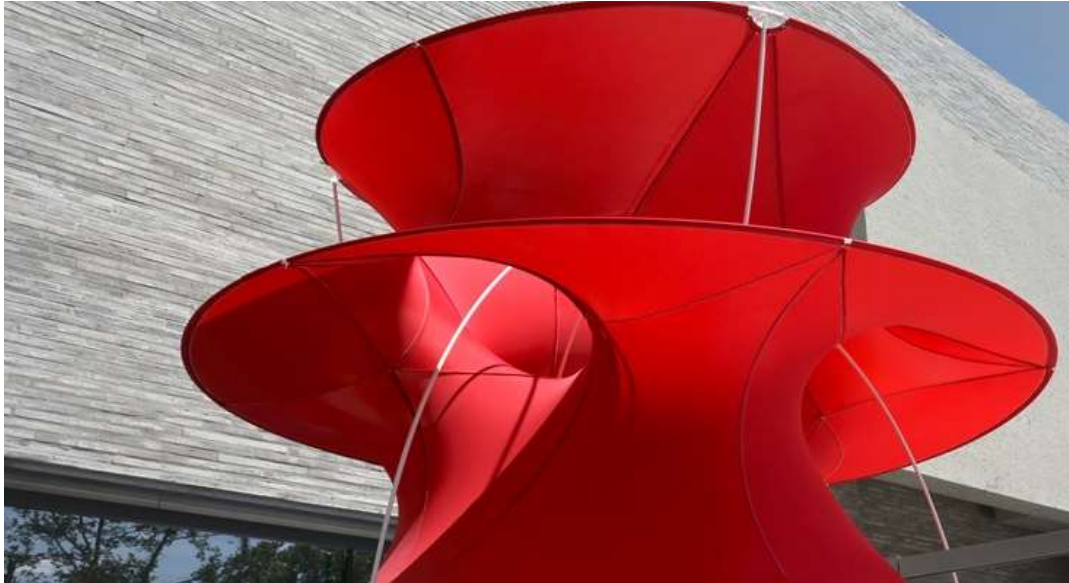








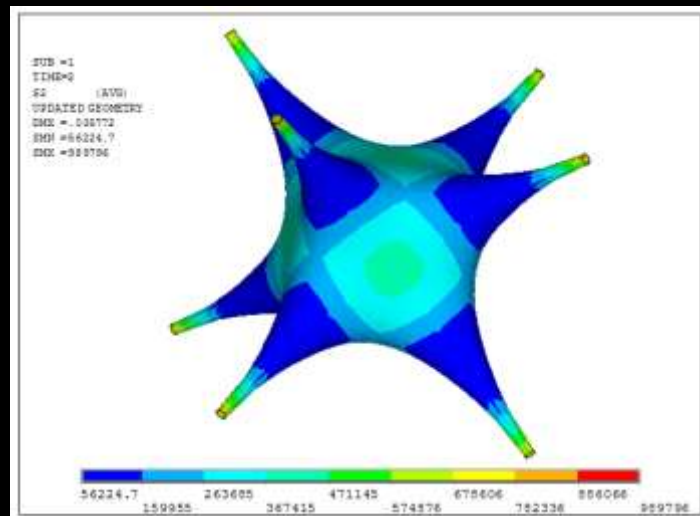
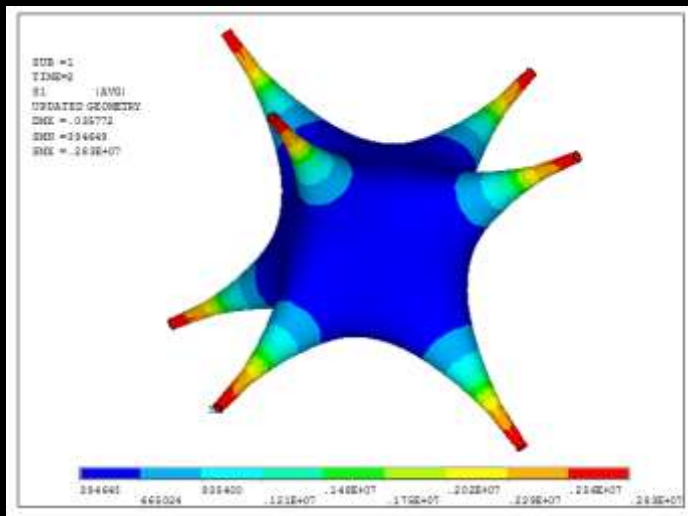
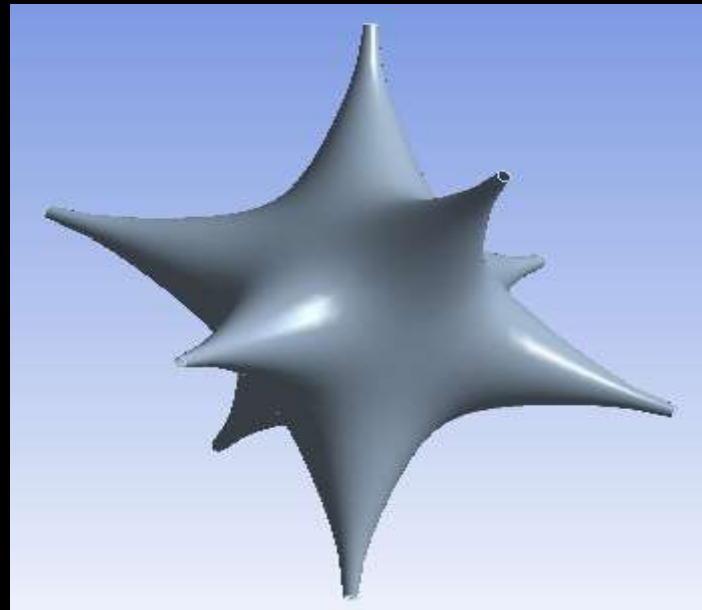
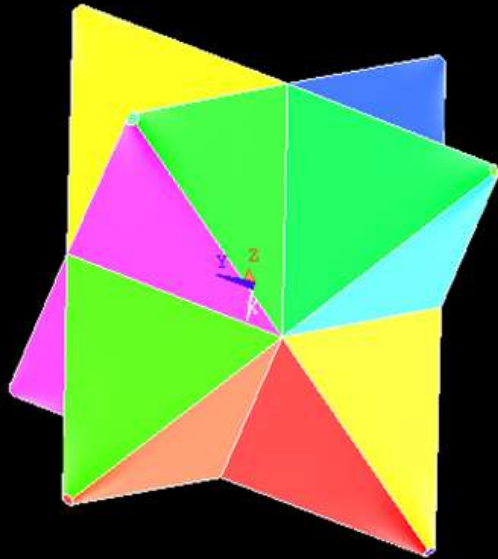
MANUFACTURING AND ASSEMBLING



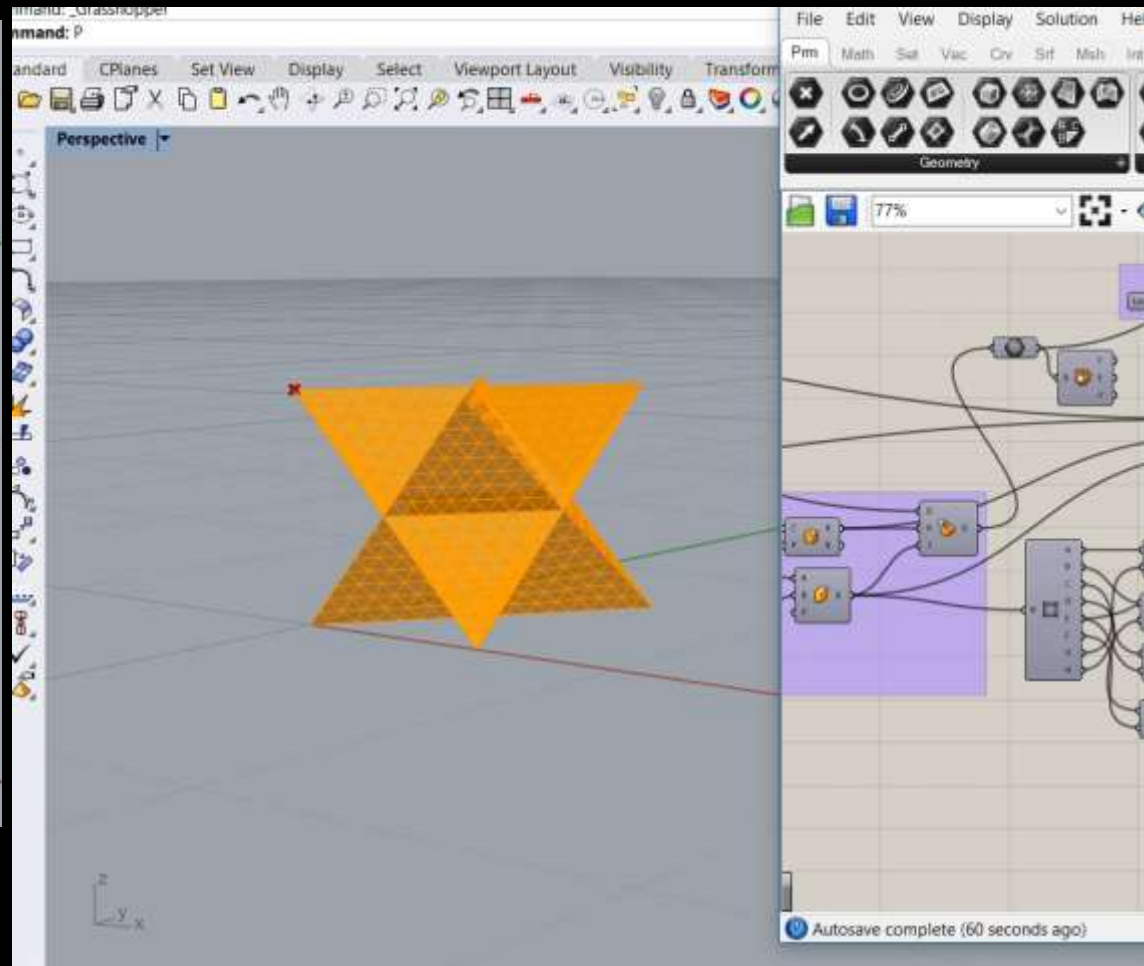
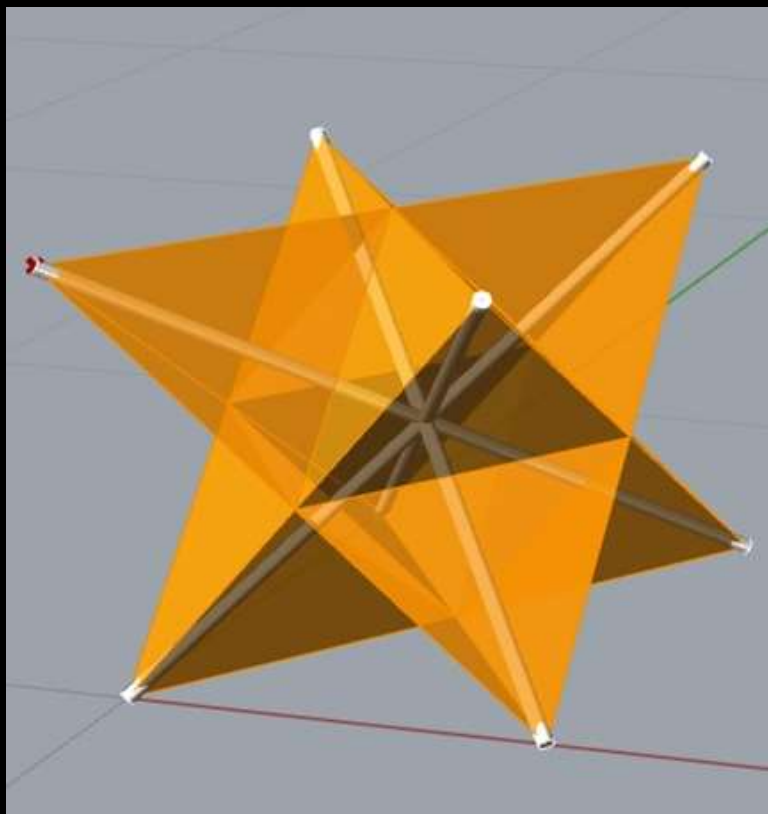
The sculpture at the hall of Hafencity main building
(Hamburg, 2017)

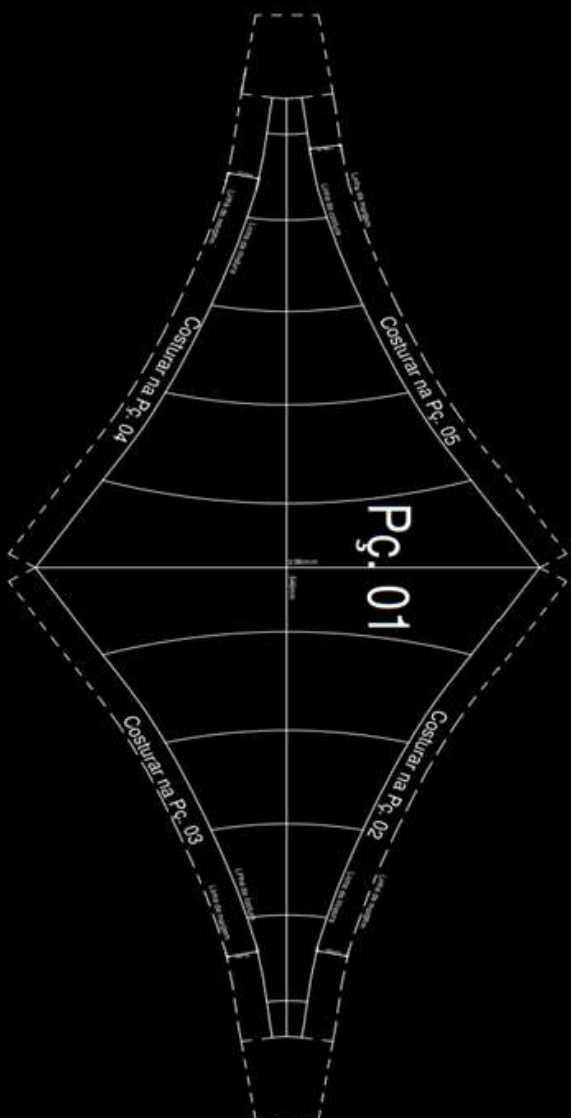


The Octahedral cusped (São Paulo, 2017)



The Octahedral cusped (São Paulo, 2017)









An Enneper surface with a Handle (Padua, 2018)



