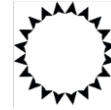




*PEF2603*  
*Estruturas na Arquitetura III -*  
*Sistemas Reticulados e Laminares*



## *“Tensoestruturas”*

*(“Estruturas Reticadas”, Redes de Cabos e Membranas)*

*(29/05/2017)*

*Professores*

*Ruy Marcelo O. Pauletti, Leila Cristina Meneghetti, Luís Bitencourt Jr.*

*1º Semestre 2017*





*Estruturas luminosas (“Light structures, structures of light” – H. Berger)*



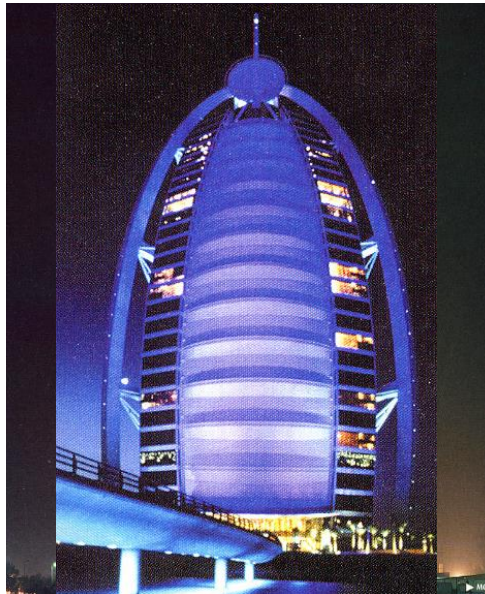




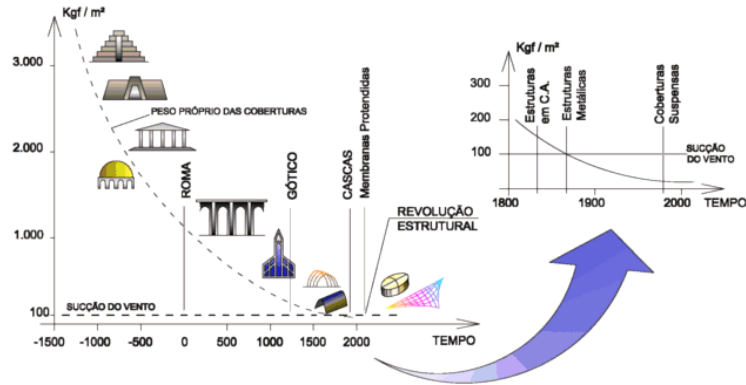


Photo by  
Tim Nugent, 2009

*'Estruturas luminosas' ("Light structures, structures of light" – H. Berger)*

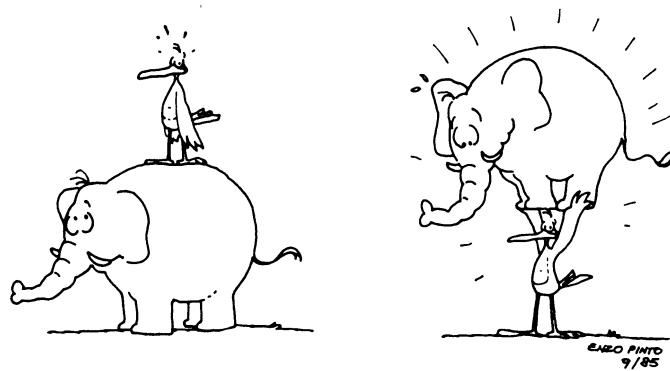


*'Estruturas leves' - "Light structures"*



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

*'Estruturas leves' - "Light structures"*



*"Peso portante << Peso portado"*  
 (Majowiecki, 1994)  
 Desenho de Enzo Pinto, Nápoles, 1985.

### *Estruturas Retesadas ("Tensoestruturas"):*

*aquelas que, para funcionarem a contento, dependem de seus elementos estarem retesados, e não frouxos.*

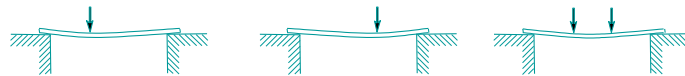
*Retesar* (v.t.): entesar, tornar tenso ou retesado, esticar, enrijar; pôr a direito. *Retesado* (adj.): entesado, enrijado, tenso, hirto, bem teso. *Retesamento* (s.m.): ato ou efeito de retesar.

[Caldas-Aulete, 1956]

*Adufe*: s.m. (s. XV) Tipo de pandeiro quadrado, de origem árabe, feito de madeira leve, com *membranas retesadas* de ambos os lados, usado especialmente em festas folclóricas portuguesas e brasileiras"

*Dicionário HOUAISS da Língua Portuguesa, Círculo de Leitores, Portugal, 2001*

### *Estruturas retesadas são 'flexíveis' :*



(a) *uma estrutura 'rígida', como uma viga, não muda drasticamente de forma, ao variar do carregamento*



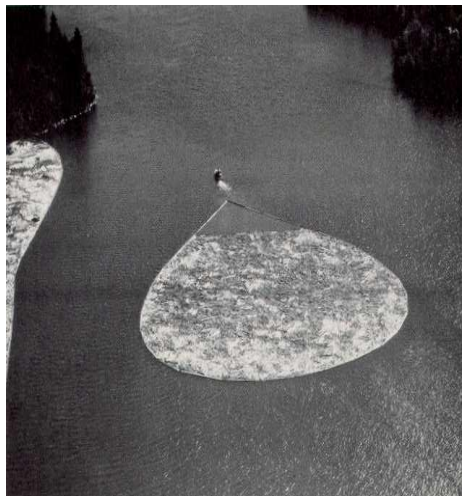
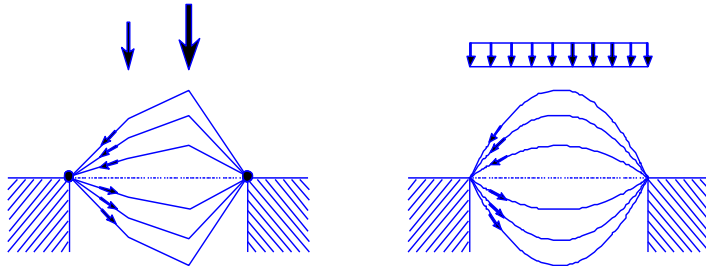
(b) *uma estrutura 'flexível', como um cabo, muda drasticamente de forma, ao variar do carregamento*



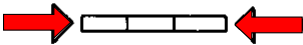
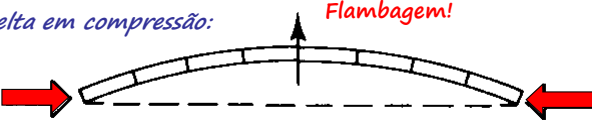
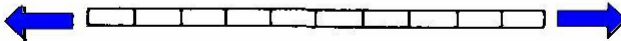
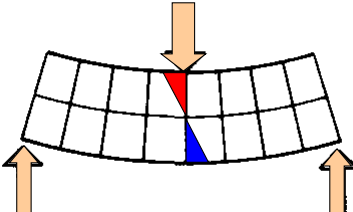
*Estruturas flexíveis devem se conformar às  
formas funiculares:*

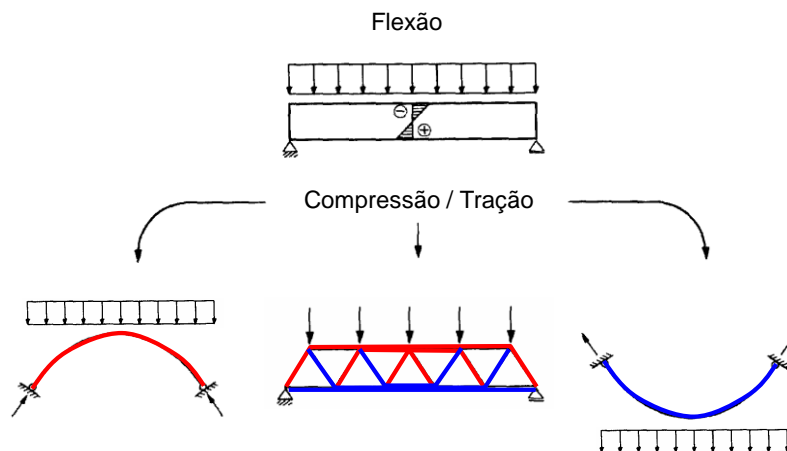
*Aquelas que equilibram um conjunto de cargas, sem o surgimento  
de esforços de flexão.*

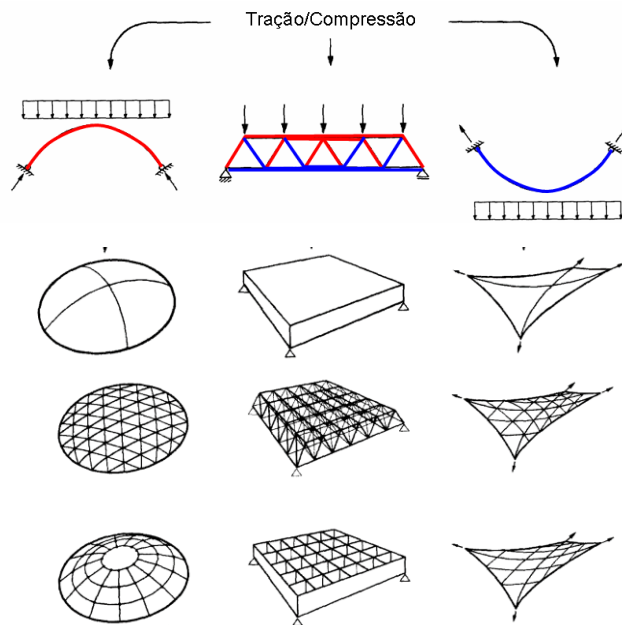
*\* Cabos e arcos:*



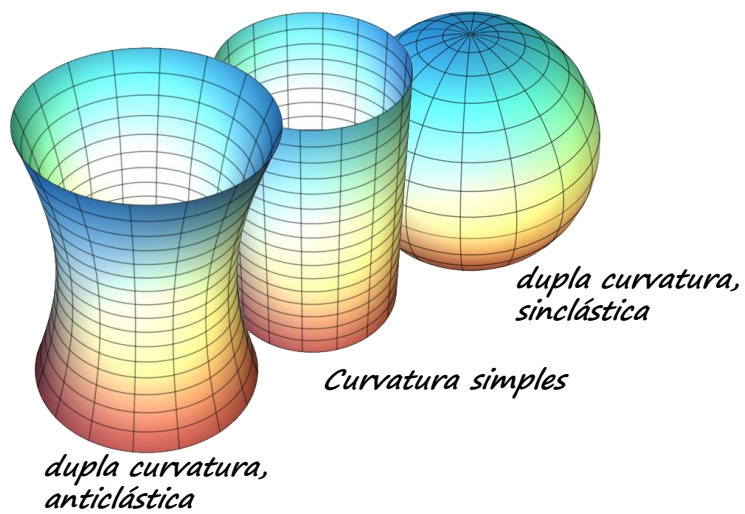
## Estados de Solicitação Interna

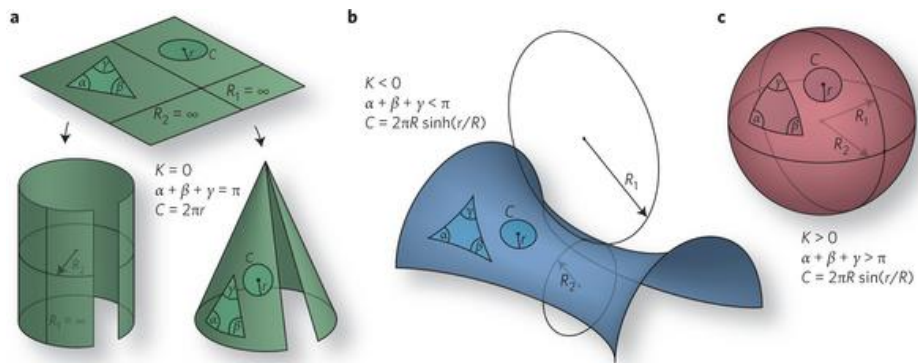
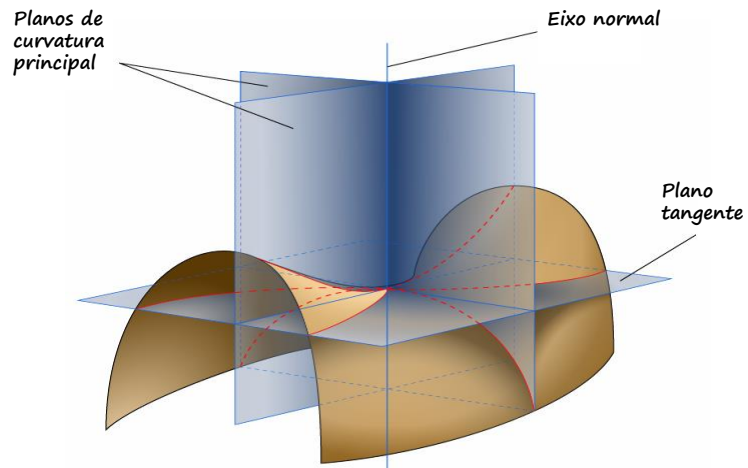
- Barra curta em compressão: 
- Barra esbelta em compressão: *Flambagem!* 
- Barra esbelta em tração: 
- Barra sujeita à flexão: 





*Superfícies de dupla curvatura:*







*Equação de Laplace-Young  
(equação das bolhas de sabão, ou das membranas):*

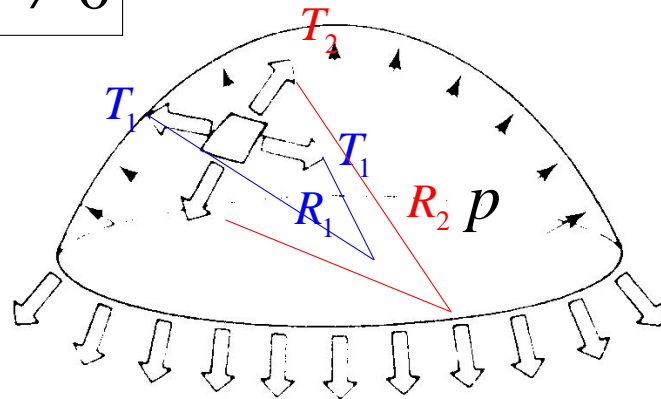
$$\frac{T_1}{R_1} + \frac{T_2}{R_2} = p$$

$\left[ \frac{kN}{m^2} \right]$

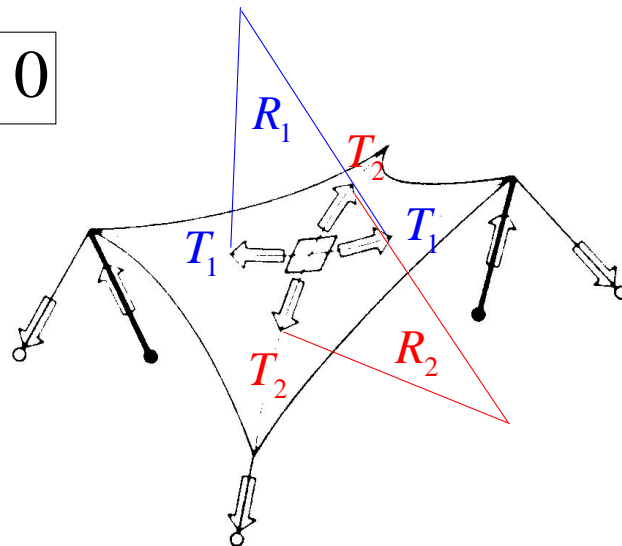
$$T_1 = t\sigma_1, \quad T_2 = t\sigma_2$$

$\left[ \frac{kN}{m} \right]$

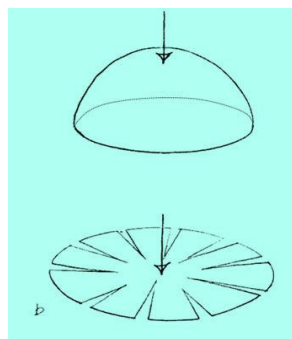
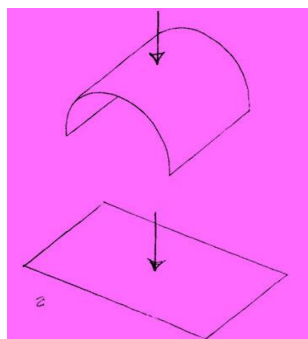
$p \neq 0$



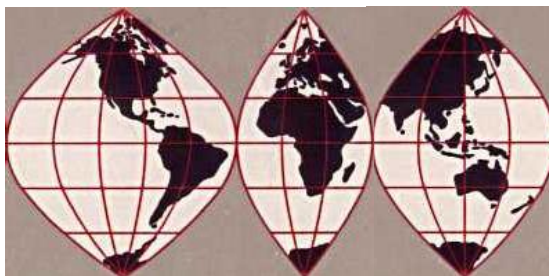
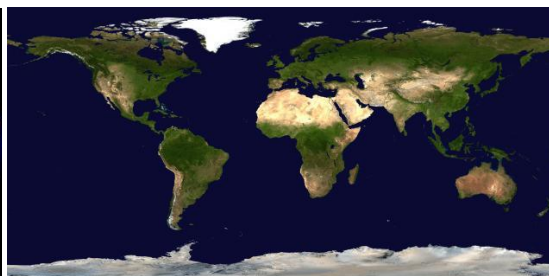
$p = 0$



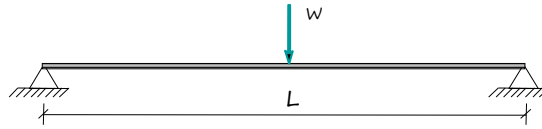
## Planificação



- a) Superfícies com uma curvatura apenas podem ser planificadas sem distorção;*  
*b) Superfícies de dupla curvatura sofrem distorção ao serem planificadas.*



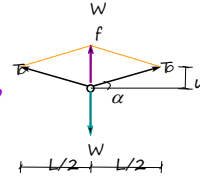
## Rigidez Geométrica



• o equilíbrio na configuração indeformada é impossível:



• o equilíbrio na configuração deformada é possível:



$$W = f = 2T_0 \sin \alpha$$

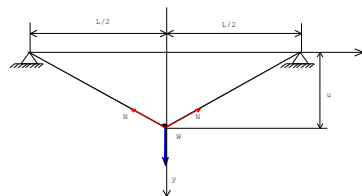
• pequenos deslocamentos:

$$f \approx 2T_0 \tan \alpha = \frac{4T_0}{L} u$$

• Rigidez geométrica, em torno da configuração inicial:

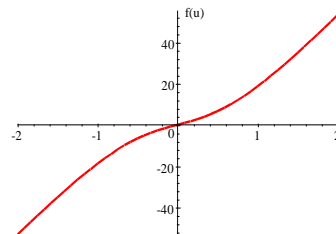
$$f = k_0 u = \left( \frac{4T_0}{L} \right) u$$

*Corda entre dois apoios fixos, carregada transversalmente, numa posição deformada*



$$k = \frac{EA}{\ell_r} \quad \ell_r < L$$

$$f(u) = 4k \left( 1 - \frac{\ell_r}{\sqrt{L^2 + 4u^2}} \right) u$$

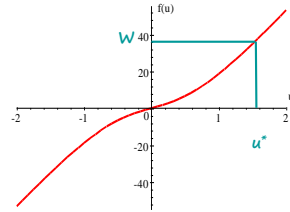




Problema não-linear do equilíbrio:

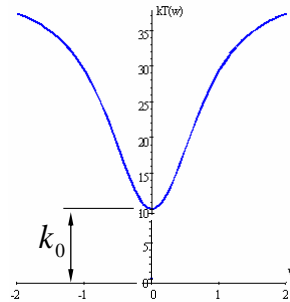
Dado  $W$ ,  $u^*$  tal que  
achar

$$g(u^*) = f(u^*) - W = 0$$



Método de Newton

$$u_{i+1} = u_i - \left( \frac{dg}{du} \Big|_{u_i} \right)^{-1} g(u_i)$$



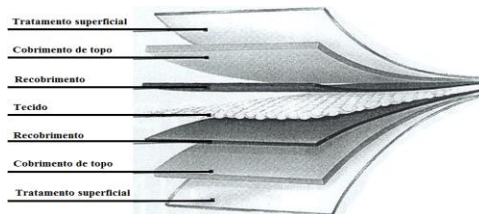
Rigidez tangente  $k_i = \frac{dg}{du} \Big|_{u_i}$



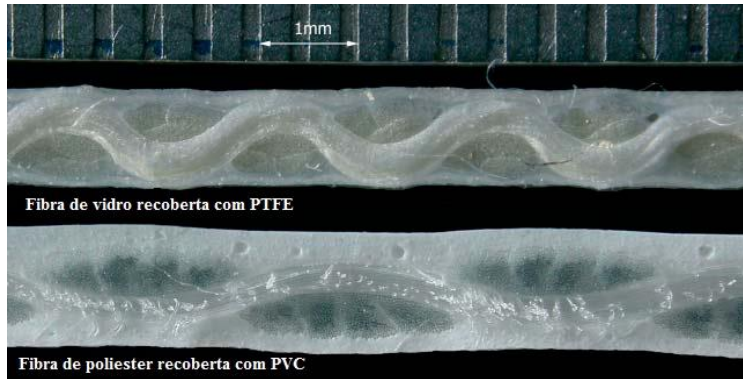
Production of a fiberglass fabric  
Pudenz (2004)



Covering with PTFE  
Pudenz (2004)



Diferentes camadas de um tecido técnico  
Blum et al (2004)

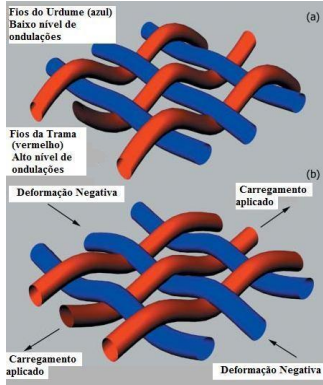


*Cross-section of fiberglass and polyester fabrics  
(BRIDGENS et al, 2004).*

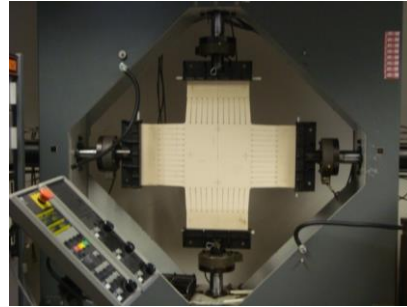
*PTFE-covered fiberglass fabric (1969)  
DuPont, Birdair, Chemfab & Owens-Corning*



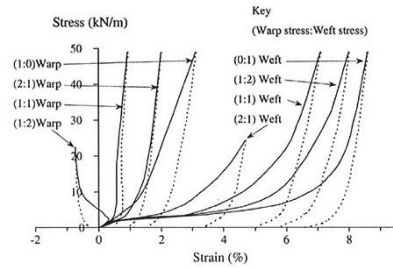
*Neil Armstrong's Suit  
Apollo 11 Project (1969)*



*Crimp Interchange, Bridgens et al. (2004).*

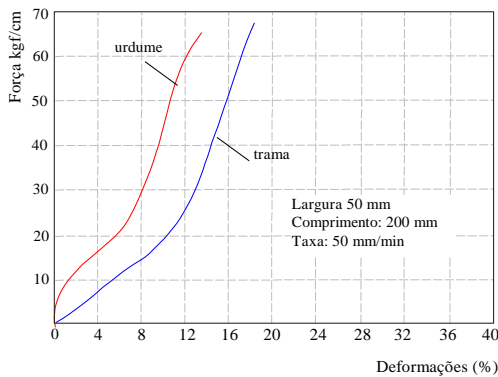


*Biaxial test (Chivante, 2009)*

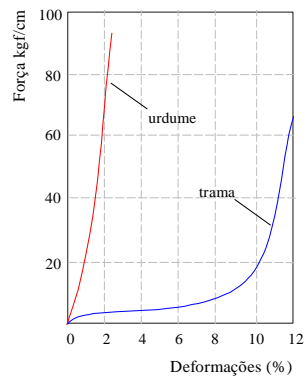


*$\sigma$ - $\epsilon$  curves for a PTFE-fiberglass fabric (warp = urdume; weft = trama), Kato et al (1999)*

## Ensaio uniaxiais (DIN 53354)



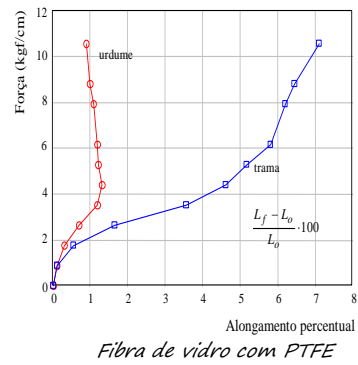
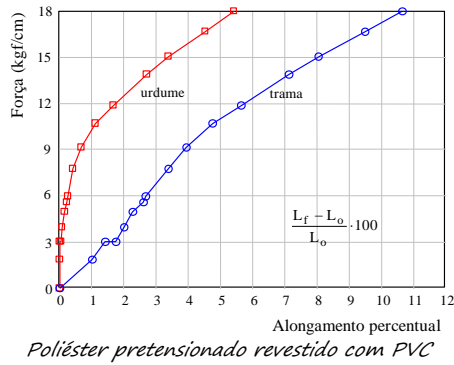
*Poliéster revestidos com PVC<sup>(a)</sup>*



*Fibra de vidro com PTFE<sup>(b)</sup>*

*Curvas típicas de força-deformação de ensaio de tração uniaxial*

## Ensaio biaxiais



*Curvas típicas de força-deformação de ensaio de tração biaxial*

### Classification of PTFE-covered fiber-glass fabrics

Type	G1	G2	G3	G4	G5	G6	G7
Tensile strenght warp/weft (kN/m)	26/22	43/28	70/70	90/72	124/100	140/120	170/158
Filament diameter (micrometer)	9	6	3	6	3	3 or 6	3
Surface weight (g/m <sup>2</sup> )	500	420	800	1 000	1 200	1 500	1 600
Trapezoidal tear warp/weft (N)			300/300	300/300	400/400	500/500	450/450



Fonte:

## PVC-covered polyester fabrics

Type	1	2	3	4	5
<b>Surface weight (g/m<sup>2</sup>)</b>					
French design guide	720	1 000	1 200	1 400	2 000
WG Messe Frankfurt	800	900	1 050	1 300	1 450
<b>Yarn linear density (dtex)</b>					
French design guide					
WG Messe Frankfurt	1 100	1 100	1 670	1 670	2 200
<b>Tensile strength warp/weft (kN/m)</b>					
French design guide	60/60	84/80	110/104	120/130	160/170
WG Messe Frankfurt	60/60	88/79	115/102	149/128	196/166
<b>Trapezoidal test warp/weft (N)</b>					
French design guide					
WG Messe Frankfurt	310/350	520/580	800/950	1 100/1 400	1 600/1 800
<b>Yarn number per cm warp/weft</b>					
French design guide					
WG Messe Frankfurt	9/9	12/12	10.5/10.5	14/14	14/14



## Comparison between different types of structural fabrics

	PVC coated polyester fabrics	PTFE coated glass fabrics	Silicone coated glass fabrics	PTFE coated PTFE fabrics
<b>Tensile strength warp/weft (kN/m)</b>	115/102	124/100	107/105	84/80
<b>Fabric weight (g/m<sup>2</sup>)</b>	1200 (type 3)	1200 (type G5)	1100	830
<b>Trapezoidal tear warp/weft (N)</b>	800/950	400/400	960/700	925/925
<b>Visible light transmission (%)</b>	10-15	10-20	< 80	19-38
<b>Flexibility/crease recovery</b>	high	low	high	high
<b>Fire reaction</b>	M2 (NFP 92 503) B1 (DIN 4102)	M1 (NFP 92 503) B1/A2 (DIN 4102)	A (ASTM E-108) no toxicity of smokes	
<b>Cleaning</b>	easier with top coats	self cleaning	self cleaning	self cleaning
<b>How to make the seams</b>	by high frequency	thermally	vulcanisation	stitching
<b>Life span (years)</b>	> 15-20	> 25	> 25	
<b>Cost</b>	low	high	high	



*Comparison of uses and costs of tension structures according to different fabric types*

Fabric type	Typical use	Cost comparison*
PTFE-coated fiberglass	Large scale permanent structures Class A ASTM E-108	\$75 – 100 per ft. <sup>2</sup>
Silicone-coated fiberglass	Large scale permanent structures Class A ASTM E-108	\$75 – 100 per ft. <sup>2</sup>
Vinyl-coated polyester	Temporary and permanent structures	\$50 – 75 per ft. <sup>2</sup>
Woven PTFE	(More pliable than standard PTFE) Retractable roofs, structures	\$85 – 125 per ft. <sup>2</sup>
ETFE	High transparency (97%) Atria, indoor parks, biospheres, skylight applications	\$100 – 125 per ft. <sup>2</sup>
HDPE (High Density Polyethylene)	Shade structures/systems	\$25 – 50 per ft. <sup>2</sup>
Laminates	Tents, awnings & canopies	\$35 – 50 per ft. <sup>2</sup>

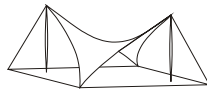
\*2008 dollars. Surface area X cost per ft<sup>2</sup> = Budget. Plan area (length X width) X Shape factor (H) = Surface area

*Fabric Architecture 2009 Sourcebook*

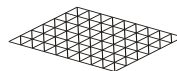


**O Processo de Projeto das Estruturas retesadas**

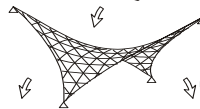
**INTENÇÃO ARQUITETÔNICA:**



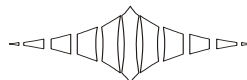
**PROJETO / ANÁLISE:**



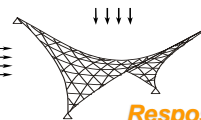
**Forma inicial, inviável**



**Forma final, viável**



**Padronagem e panificação**

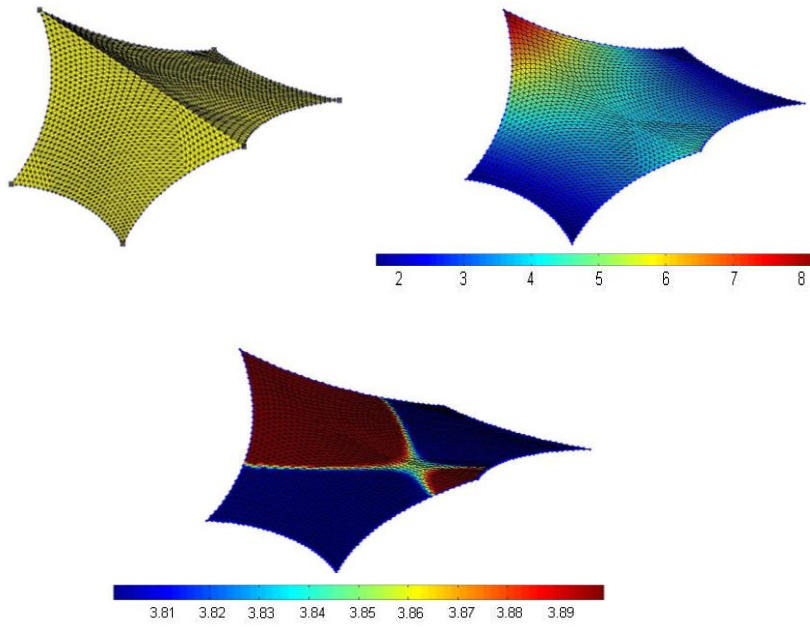


**Resposta aos carregamentos**

**SOLUÇÃO DE PROJETO**

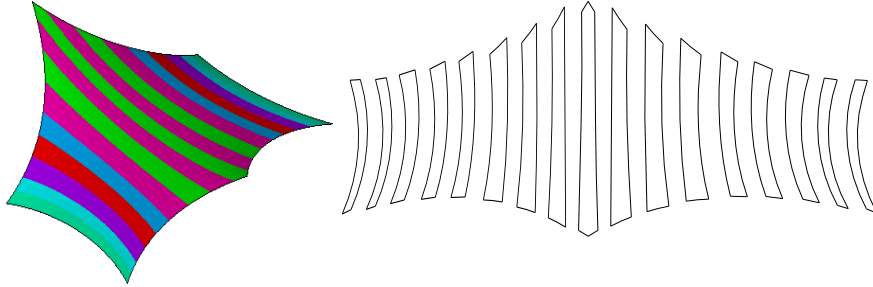


The membrane roof of the “Memorial dos Povos”  
of Belém do Pará

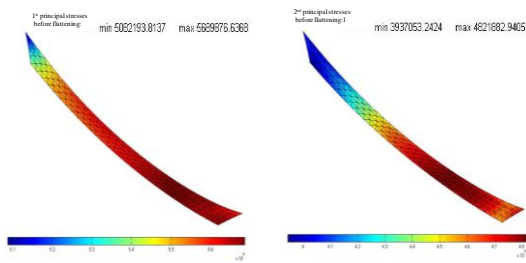




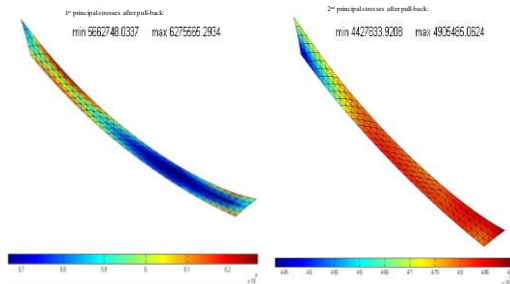




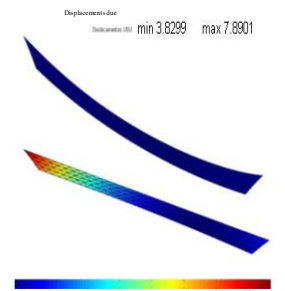
*Cutting patterns*



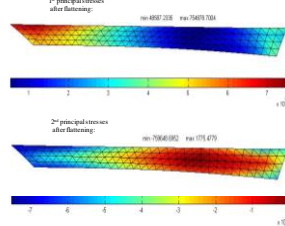
*Initial prestresses*



*Stresses after pull-back*

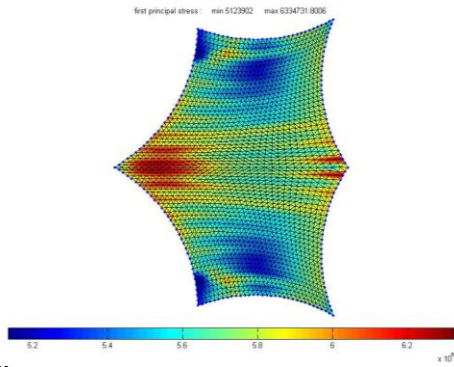


*Flattening process*

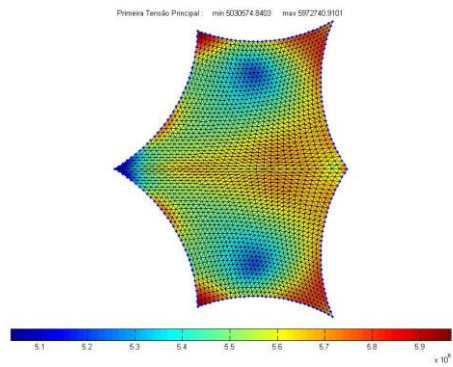


*Residual stresses*

R  
·  
M



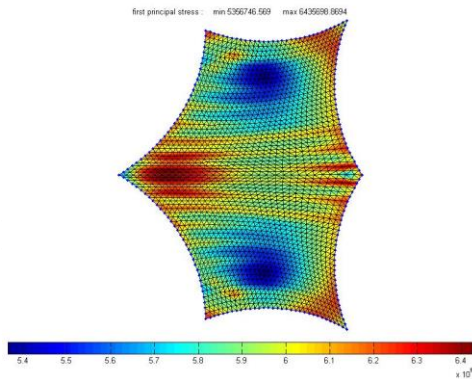
*Maximum first principal stresses after planification and pull-back*



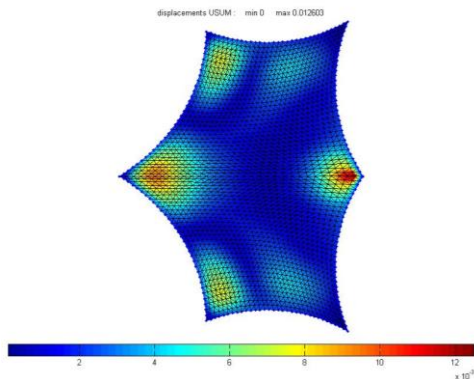
*Maximum first principal stresses for the prestress load case, as initially calculated*

·  
w  
·  
i  
·  
m  
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c  
·  
e  
·  
p

R  
·  
M



*Maximum first principal stresses after relaxation of pull-back stresses*



*Displacements due to relaxation of pull-back stresses*

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i  
·  
m  
·  
c  
·  
e  
·  
p

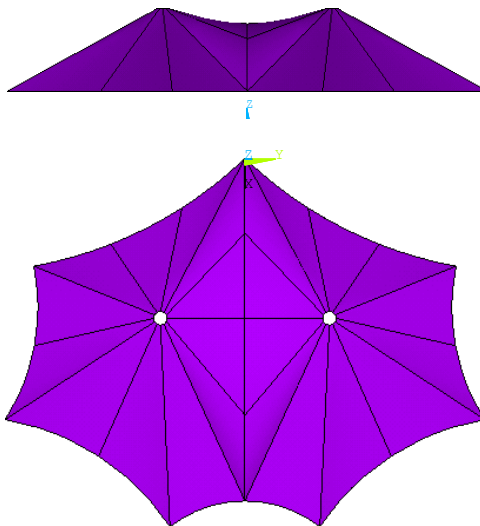
Cobertura em  
Membrana Retesada  
**Igreja Batista Central  
Fortaleza  
(2004)**



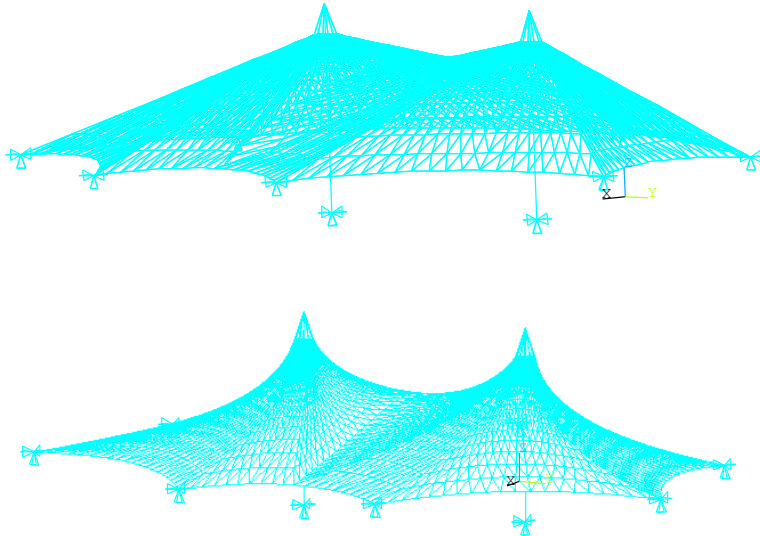
**Concepção Arquitetônica:**  
Nasser Issa Arquitetos Associados

**Projeto e Análise Estrutural da Membrana:**  
Ruy Marcelo Pauletti  
Reyolando M.L.R.F. Brasil

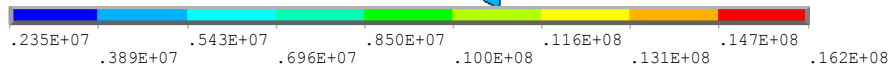
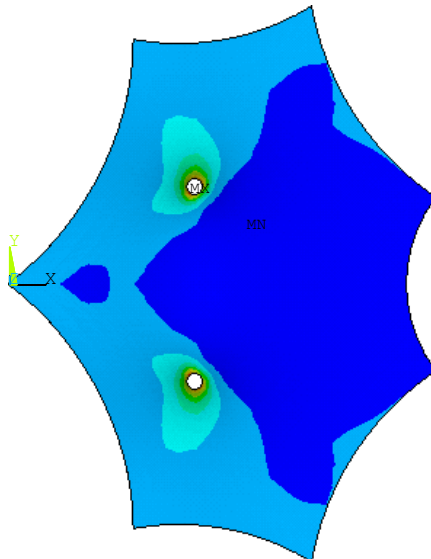
**Estrutura Metálica:**  
Paulo André Barroso



R  
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P  
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t  
i  
-  
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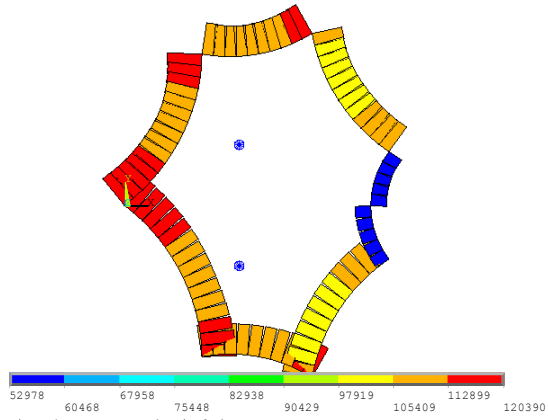


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S1 (AVG)  
DMX =.247158  
SMN =.235E+07  
SMX =.162E+08

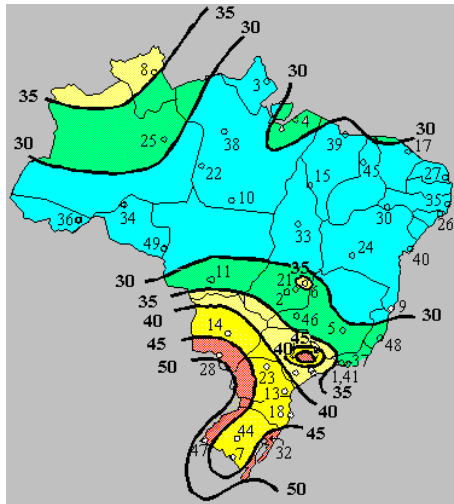


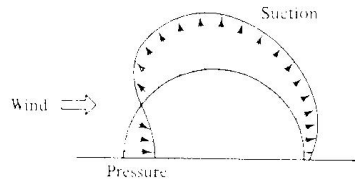
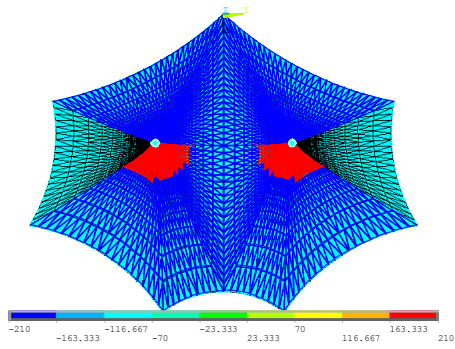
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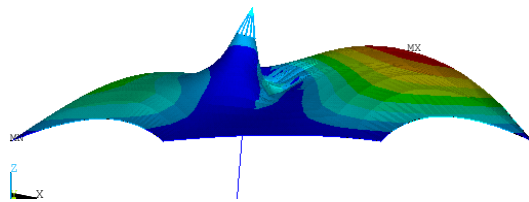
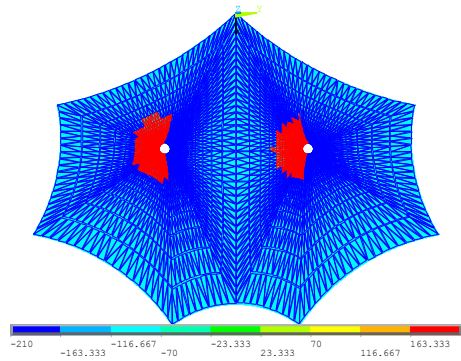


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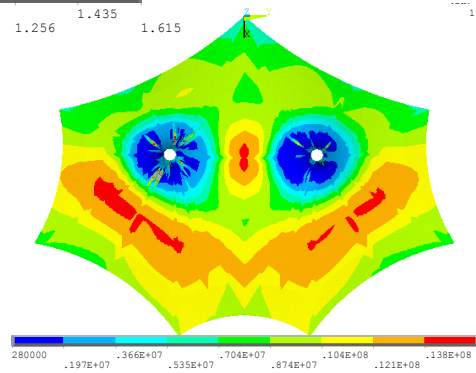


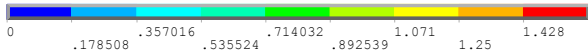
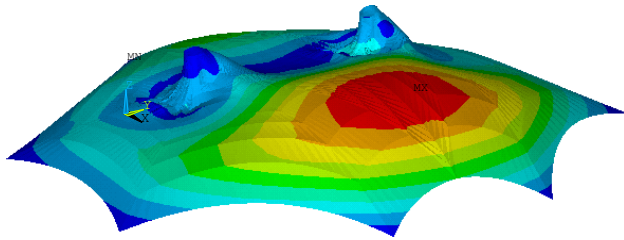


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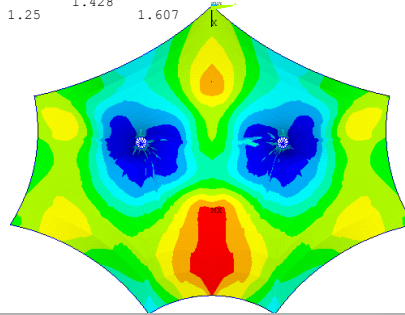


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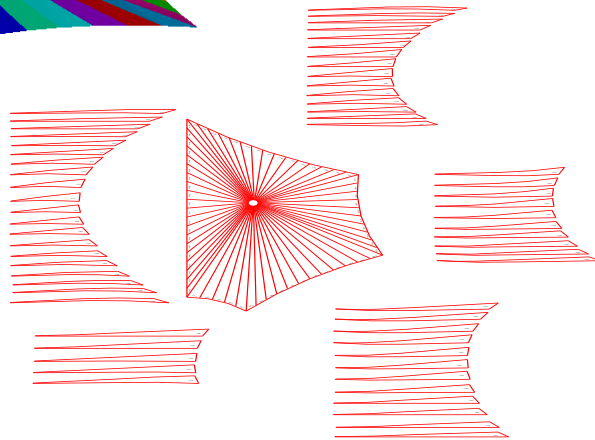
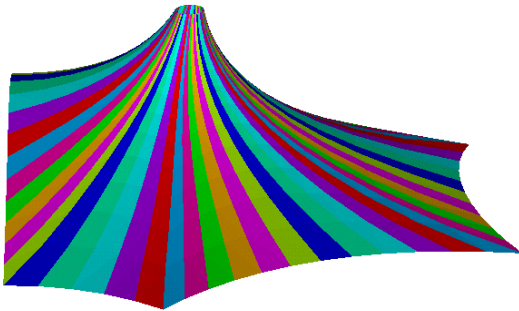




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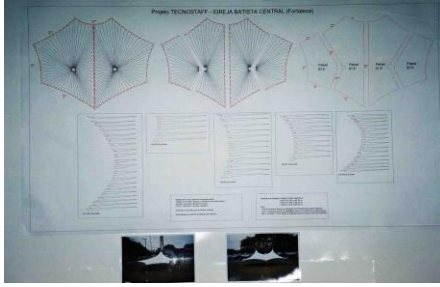


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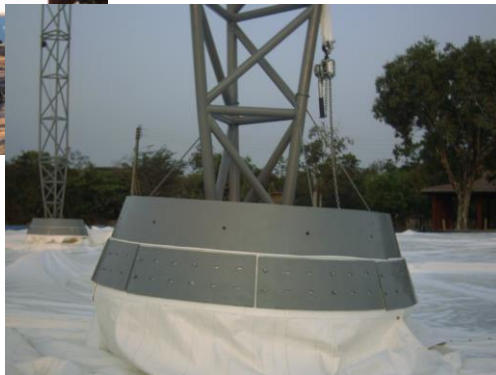
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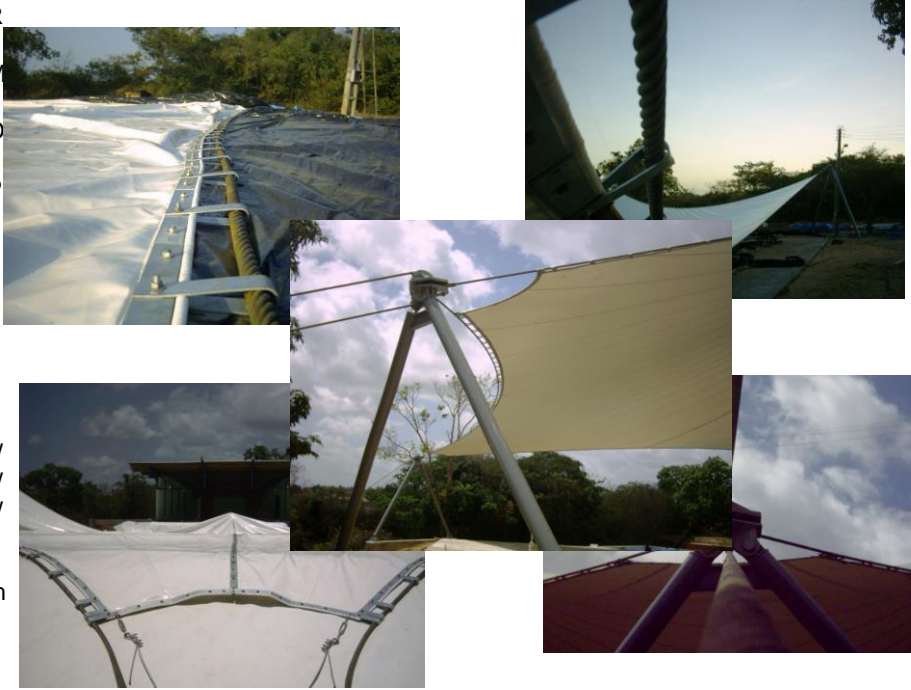




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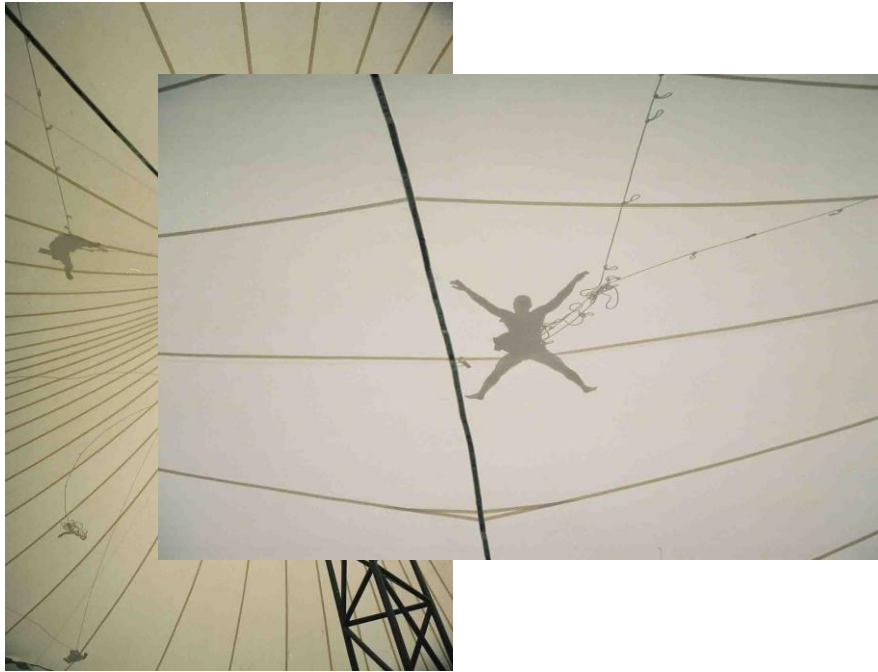
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*Ruy Marcelo de Oliveira Pauletti*

*Polytechnic School of the University of São Paulo*

## **Design and Construction of Goiânia's Open Market**



**2006**



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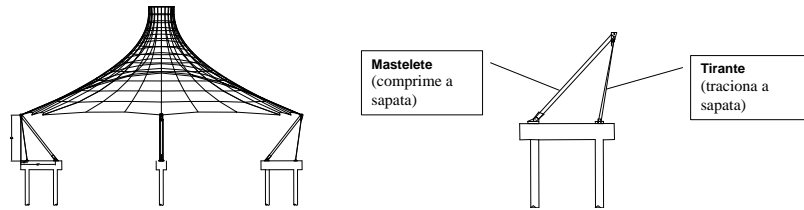
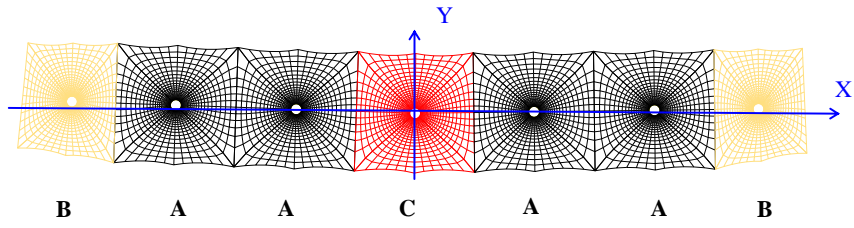


R · M · O · P a u l e t t i - w w w · l m c · e p

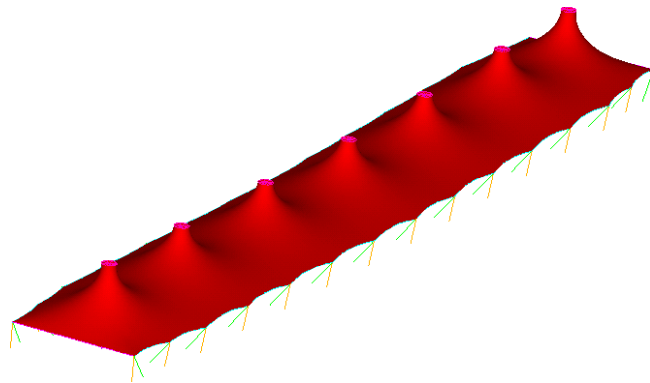


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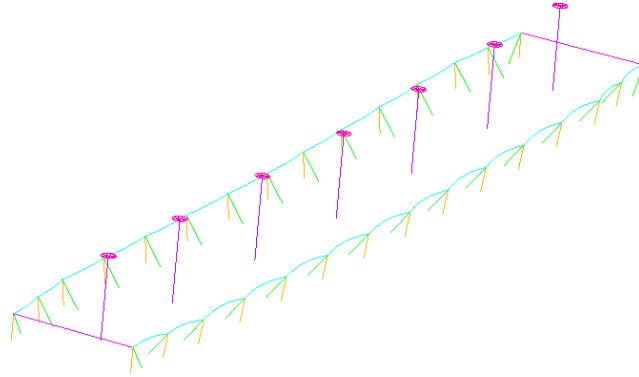




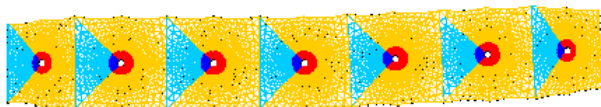
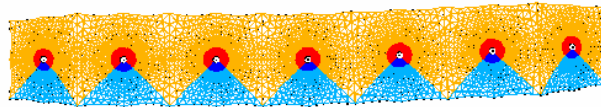
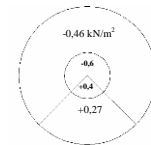
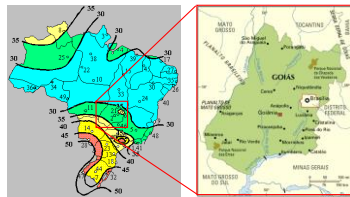
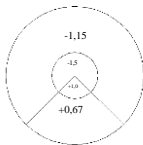
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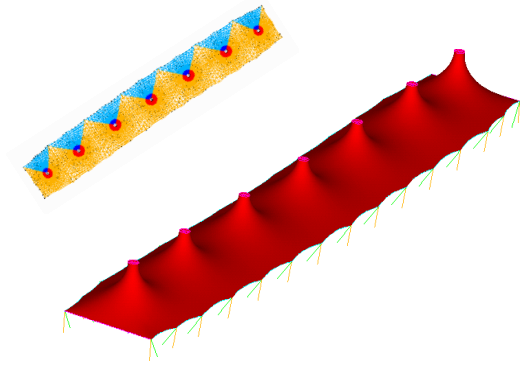
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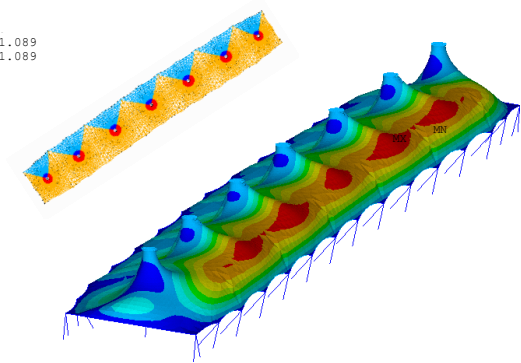


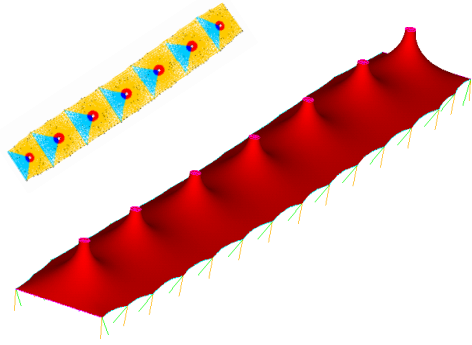
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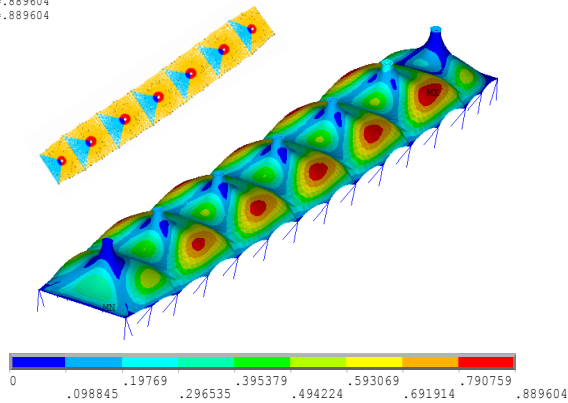
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DMX =1.089  
SMX =1.089

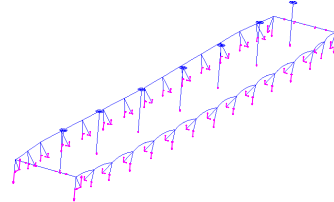
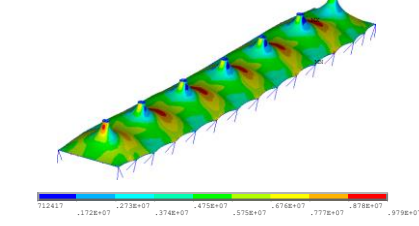
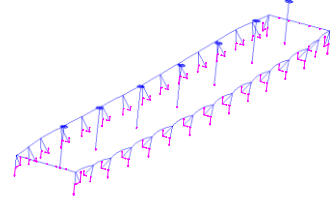
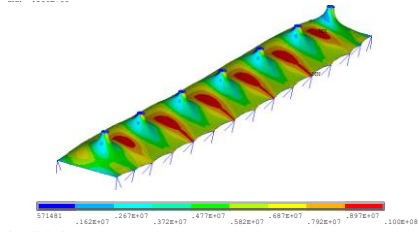
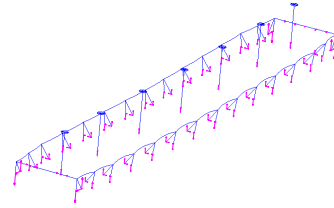
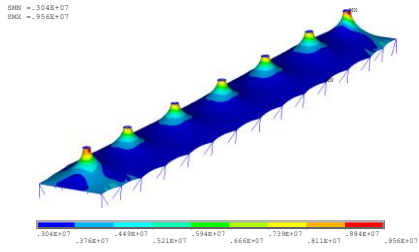




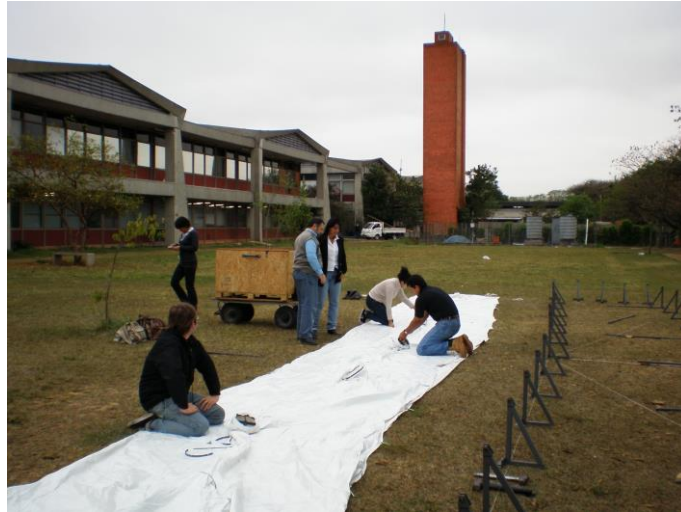
DMX = .889604  
SMX = .889604



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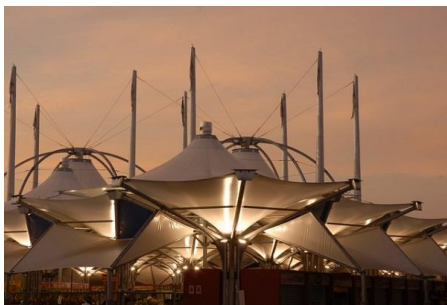
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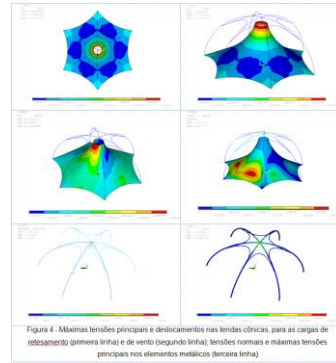




"Feira da Cidade de Ananindeua, PA (2006)  
Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento



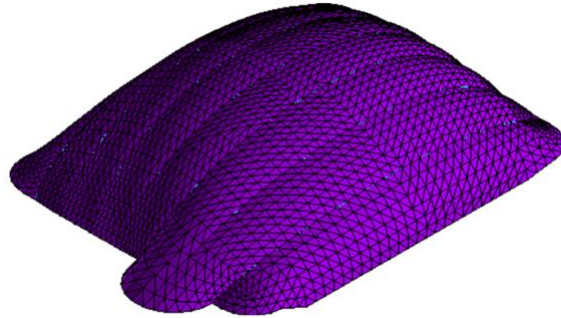
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Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento



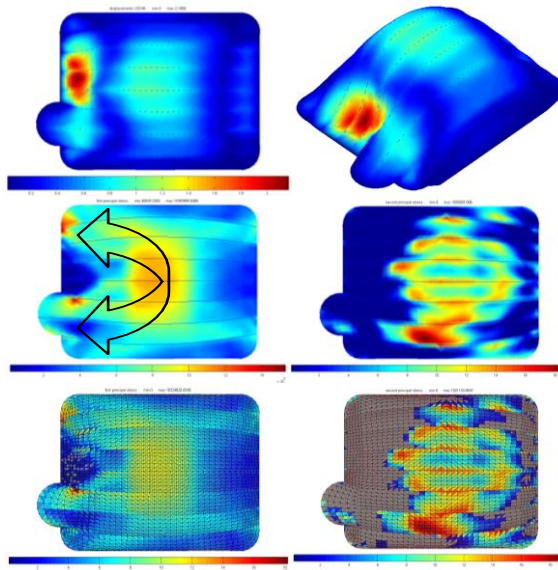
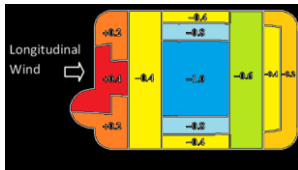
"Feira da Cidade de Ananindeua, PA (2006)  
Arch. José Maria Coelho Bassalo and Flávio Campos do Nascimento







Longitudinal wind,  
adherent cables



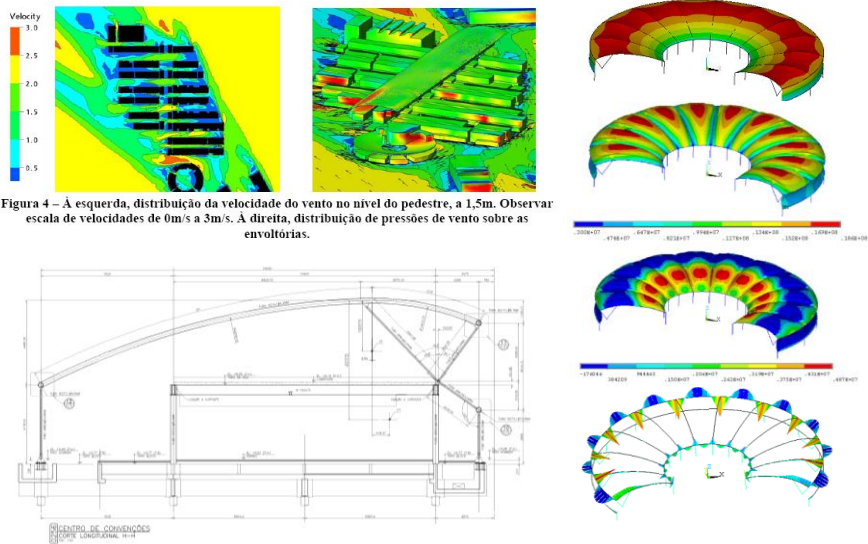
(a) field of displacement norms; (b) *idem*, isometric view; (c) stress field; (d) stress field.

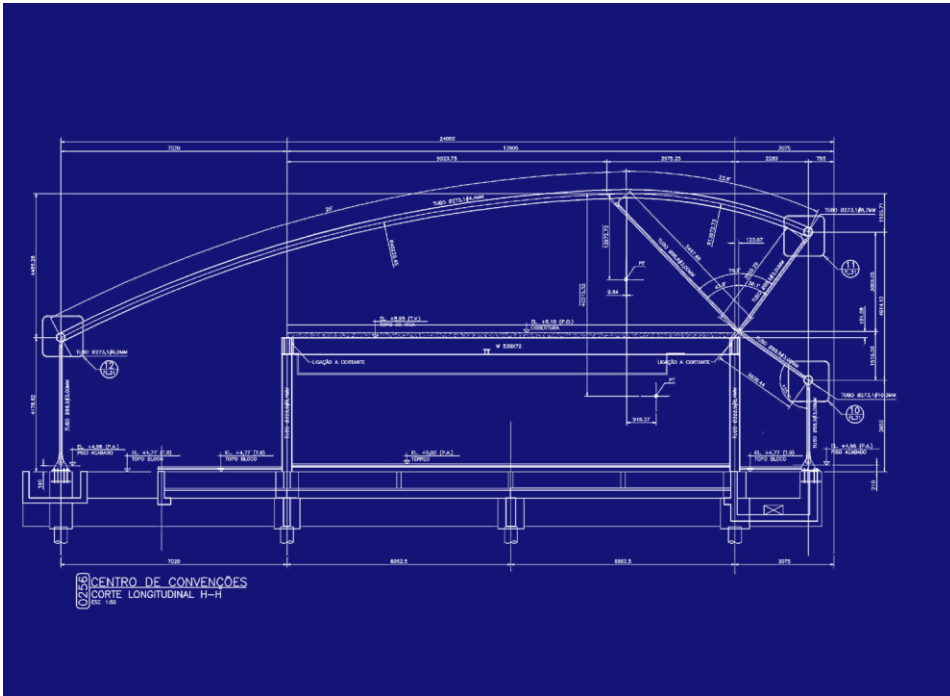






## CENPES II





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

Designers:

(1) Nelson Fielder

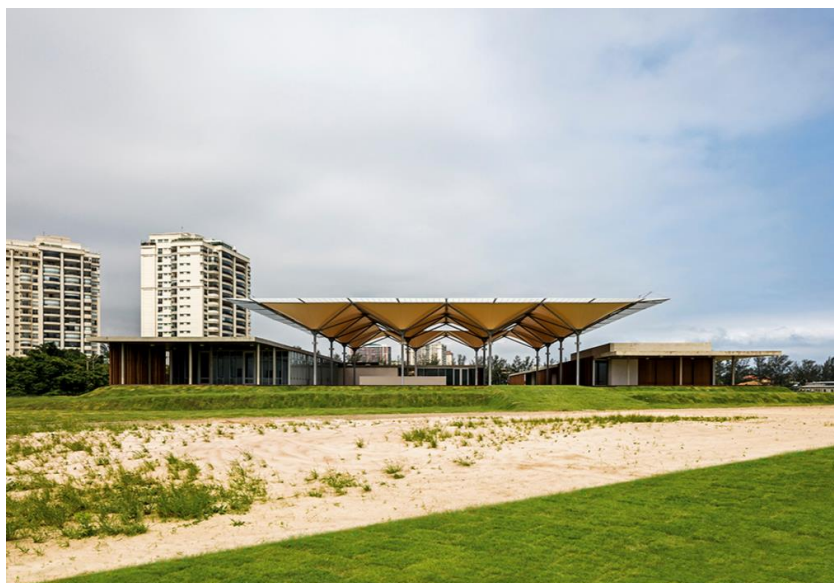
(2) Pedro Marcelo Paín de Santana



*Sede do Campo Olímpico de Golfe / RUA Arquitetos  
(Pedro Évora, Pedro Rivera) 2015/2016*



*Sede do Campo Olímpico de Golfe / RUA Arquitetos  
(Pedro Évora, Pedro Rivera) 2015/2016*



*Sede do Campo Olímpico de Golfe / RUA Arquitetos  
(Pedro Évora, Pedro Rivera) 2015/2016*

