STRUCTURAL ANALYSIS AND CONSTRUCTION OF THE MEMBRANE ROOF OF THE “MEMORIAL DOS POVOS DE BELÉM DO PARÁ”

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ABSTRACT: This work presents the numerical and physical models developed during the design of the membrane roof of the amphitheater of the “Memorial dos Povos de Belém do Pará” (MPBP), as well as the fabrication and construction of the actual membrane. The MPBP is a new public space, recently opened by the City of Belém (main city of the State of Pará, Brazil), and is directed to cultural activities. The amphitheater’s roof is composed by a saddle shaped membrane, with two high points and for low points, symmetrical respect to the ridge axis. The roof has an area of about 400m^2, and its horizontal projection can be inscribed in a 23m x 29m rectangle. The paper outlines the procedures to form finding, stress analysis and patterning of the membrane, as well as the determination of cables and anchor loads. Numerical models were developed with the aid of the Ansys finite element code. Response to prestress and wind loads was verified for several cases. Physical models were produced to validate patterning, manufacturing, erection and pre-stressing procedures.

Keywords: membrane structures, structural analysis, finite element method, construction.

INTRODUCTION

The amphitheater of the “Memorial dos Povos de Belém do Pará” (MPBP), is located in a new public space of the Belém, capital city of the State of Pará, Brasil, recently opened by the City of Belém (main city of the State of Pará, Brazil), and is directed to cultural and leisure activities, and commemorates the immigrants, from many different origins, that melted to originate the Amazonian people. The whole complex of buildings has about 6.000m^2 and includes a multipurpose indoor theater and restaurant, besides the amphitheater whose roof is of concern to this paper.

The initial geometric parameters considered for the development of the analyses described herein have been extracted from drawings issued by the Public Authority of Belém City, and provided to the authors of this paper by the contractor of the analyses presented herein (*Technostaff Engenharia e Estruturas*).

The original architectonic intention for the membrane roof of the MPBP, as devised by the Architectural Project, is shown in Figure 1. The roof is composed by a saddle shaped membrane, with two high points contained in a vertical symmetry plane, and four lower points the same height. The horizontal projection of the roof could be inscribed in a 22.6m by 28,6m, and total area amounts to 399m^2. During the structural analyses, some minor geometric modifications were introduced in the design, and are described in the sequel.

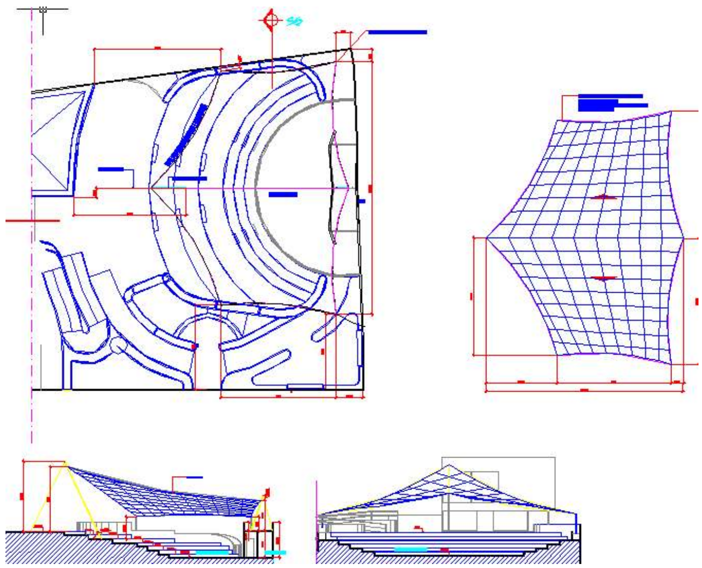

Figure 1. Architectonic intention for the membrane roof of the "Memorial dos Povos de Belém do Pará"

STRUCTURAL ANALYSIS OF THE MEMBRANE

The process of structural analysis, from the form finding to the development of physical models has been previously described in several references (Pauletti, 1999, 2001, 2002, 2003A/B). As is typical in the design and analysis of tension structures, the work involves an initial phase of form finding, a compromise is sought between structural, architectonic and site requirements. Once a viable shape has been determined, the response of the membrane to wind design loads is inspected, and adequate cutting patterns are finally generated. In the case of the MPBP, the process required four revisions finally achieving the determination of satisfactory membrane geometry, stiffness and stress field, as well as loads on cables and anchors, namely the king and queen poles, and the four lateral tripods. In this work, only the final design results are discussed.

Respect to the original architect's intention, already shown in Figure 1, the main modification was a 1.0m increase in the height of the king and queen poles, in order to increase the declivity of the membrane and thus facilitate rainwater flow. However, even with these increase in height, the average curvature of the membrane was deemed too small to guarantee enough membrane stiffness to transversal loads. Thus, a high prestress level was assigned, which by its turn, required an increase on the curvature of the border cables, in order to moderate the tractions acting on them. Also, considering the necessity of providing enough stiffness to the anchor loads, the slender lateral columns which were originally devised by the architect's intention were replaced by metallic tripods, probably more economic than the original columns. Besides, the columns would introduce undesirable bending moments on the foundations, complicating their dimensioning and detailing.

All the structural analyses of the membrane were performed with the aid of the Ansys finite element code. Geometric nonlinear, large displacement analysis options were required. Fully Newton-Raphson method was adopted for solution. The membrane was discretized by constant strain, triangular elements (SHELL41), working exclusively on tension. Cables and masts were modeled with truss elements (LINK8). Linear isotropic materials were assumed.

LOADS

The structural analysis of the MPBP membrane roof took pre-stress and wind loads into account. It was assumed that wind loads offered also a good envelope for rainwater loads. Self-weight of the membrane fabric was disregarded. Three load cases were considered, as follows.

1. **Prestressing loads**: A sufficiently high stress field imposed along the membrane during the assembling process, stretching stays and border cables, in order to compensate the membrane's low mean slope.
2. **X-wind loads**: pressure loads due to wind blowing parallel to the membrane's ridge, combined with prestressing loads.
3. **Y-wind loads**: pressure loads due to Wind blowing transversely to the membrane's ridge, combined with prestressing loads.

Basic wind pressure was defined acordign to Brazilian NBR-6123/88 Code, considering mean wind velocity v_o*=30m/s* (Belém do Pará), low slope terrain, 10m average height, and high occupancy. That leads to a design velocity of V_k= *24m/s* and thus $q = 0,613V_k^2 = 286N/m^2$.

There are no specific pressure coefficients prescribed in the Brazilian code to ridged, saddle shaped membranes, so a rough analogy with a plane roof with two slopes was adopted. Thus, for a wind blowing normal to the membrane's ridge (Y-wind), windward compression $q = 286N/m^2$ and lee-side suction $q = -115N/m^2$ were adopted, whilst for a wind parallel to the ridge (X-wind), a uniform suction $q = 286N/m^2$ was adopted for both slopes.

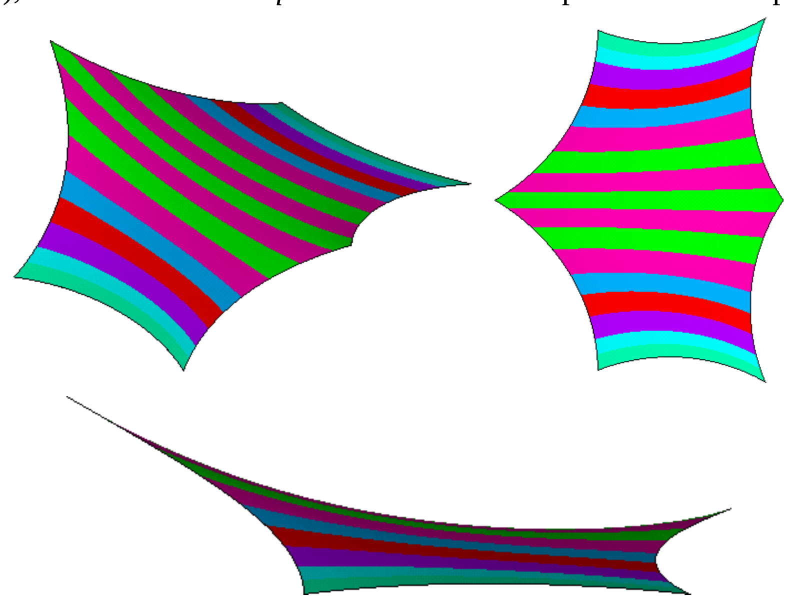

Figura 2. Geometry of the membrane of the roof of the 'Memorial dos Povos de Belém do Pará', with fabric pattern highlighted by colors.

RESULTS

Figure 2 shows the geometry of the membrane resulting from the shape finding process, already with the several strips of fabric (maximum width 4.5m), reinforced by colors. Figure 3, by its turn, shows the contour levels along the membrane, highlighting the saddle point that guarantees a 15% minimum average slope, enough to allow draining rainwater.

Figure 4 shows the location of the membrane anchors, corresponding to the tops of the king and queen posts and of the four lateral tripods. It is supposed that both poles are articulated at their bases and stayed by single cables, being laterally stabilized by the membrane's border cables. I is also supposed that border cables between the fixed tripods will be stretched by means of turnbuckles.

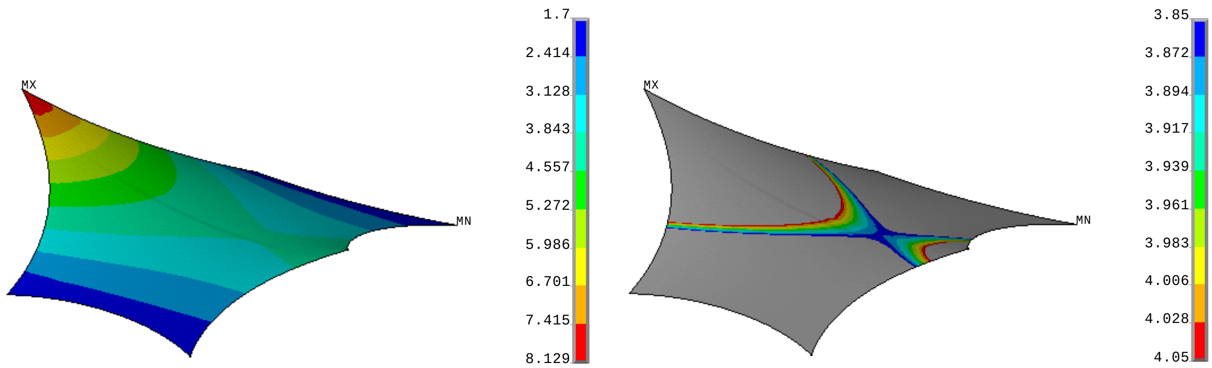

Figura 3. Geometry of the membrane of the roof of the 'Memorial dos Povos de Belém do Pará', showing contour levels and membrane's saddle point.

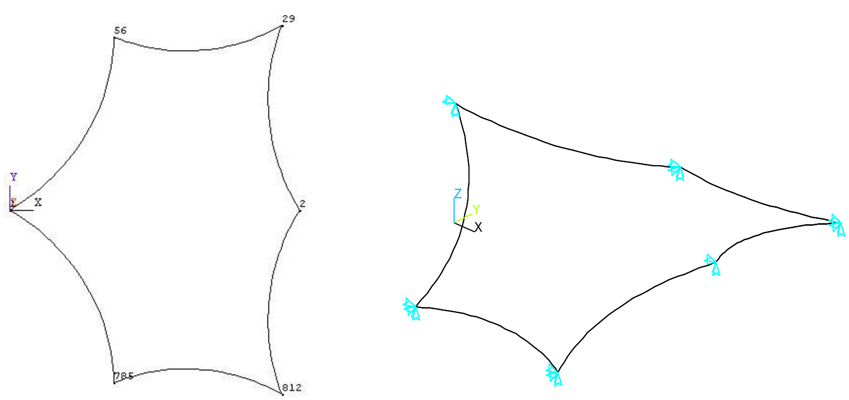

TABELA 1. COORDENADAS DOS PONTOS DE ANCORAGEM (topo dos mastros 'rei' e 'rainha' e topo dos tripés			
Nó (Ponto)	X [m]	Y [m]	Z [m]
1 (Mastro Rei)	0.0000	0.0000	8.3700
2 (Mastro Rainha)	22.590	0.0000	4.5600
29 (tripé)	21.190	14.320	1.6500
56 (tripé)	8.0700	13.380	1.6500
785(tripé)	8.0700	-13.380	1.6500
812 (tripé)	21.190	-14.320	1.6500

Figura 4. Anchor points, and corresponding finite element nodes and displacement restrictions.

In the case of the **prestressing loads**, the maximum tension stress in the membrane reached 7.4MPa (or 7.4kN/m, for a 1mm thick fabric), in the queen pole vertex, with an average stress of de 5.0MPa (or 5.0kN/m) along most of the membrane span. Knowledge of anchor reactions due to prestressing, are fundamental to erection of the membrane, since they are precisely the loads to be aplied by the prestressing system. Maximum anchor loads reached 150kN, at the top of the king post.

In the **X-wind** case, the maximum principal stress reached 13MPa (or 13kN/m), close to the membrane's saddle point, whilst in the case of **Y-wind**, maximum principal stress reached about 10MPa (or 10kN/m), again close to the membrane's saddle point. In all loading cases, maximum stress values are reasonably bellow the 100kN/m uniaxial strength reported by the *Mehler Haku type III* fabric adopted. Models also did not accused slackening of the membrane in any of the studied load cases, with positive minimum principle stresses along all the membrane. Maximum displacements due to X-wind loads reached about 0.38m, at mid-span of both slopes; whilst the Y-wind loads provoked a 0.43m upward displacement at mid-span of the lee-side slope. Due to the inherent flexibility of membrane structures, these displacements were considered satisfactory.

Dimensioning of the metallic and concrete structural elements is not discussed in this paper. It is important to point out, however, that anchors shall be designed to withstand the prestressing loads, as well as the envelope of the loads due to the X-Wind and Y-Wind load cases. Also, besides ensuring strength, the design of metallic structures has to ensure enough stiffness to these elements, in order that the stiff anchor hypothesis adopted in the membrane analyses is fulfilled, for practical purposes. Another requirement, for the subsequent design phases, was the preservation of the membrane geometry, although a rigid body shift could be applied. Indeed, a 1.5m upward shift was imposed to the whole membrane, during the design of the supports.

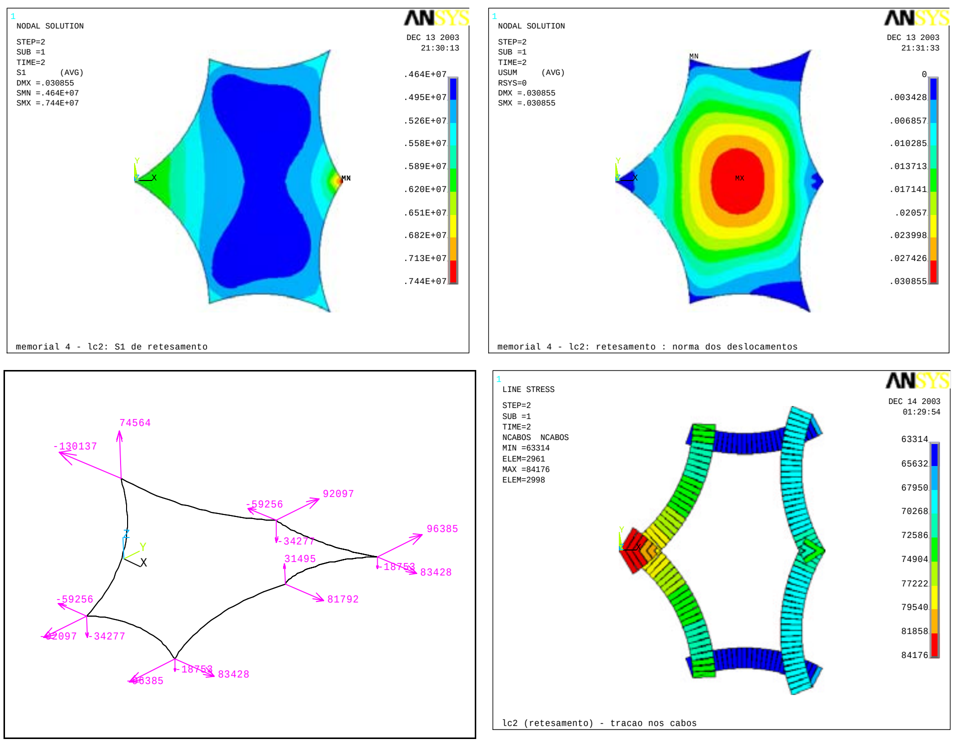

Figura 5. Maximum first principal stresses along the membrane (S1), displacement norms (USUM), anchor loads and traction on border cables (Ncabos), for the prestress load case.

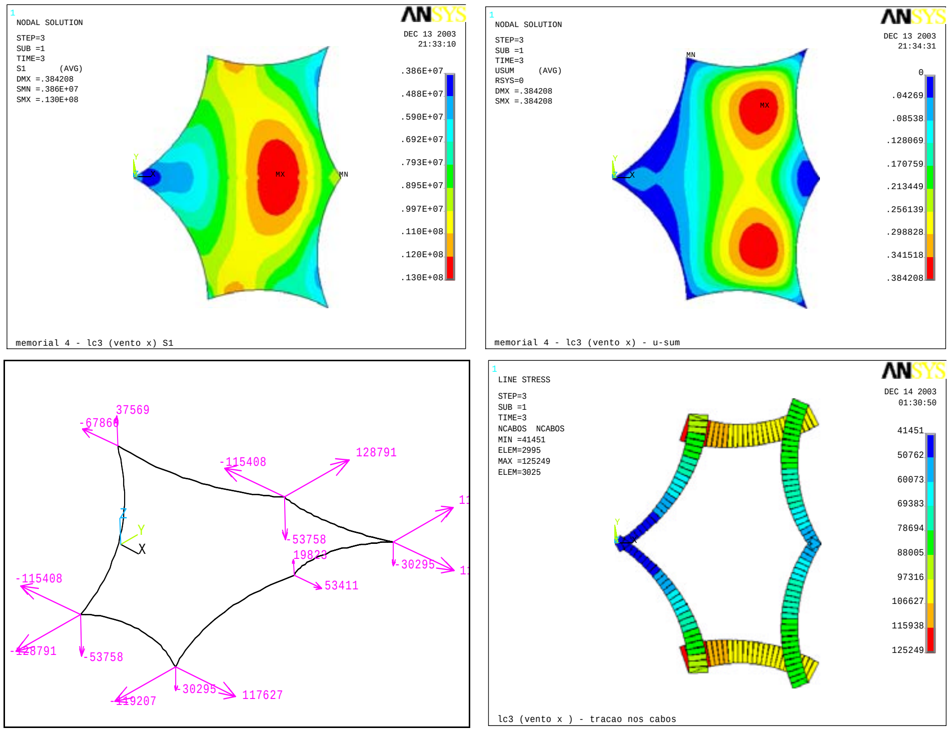

Figura 6. Maximum first principal stresses along the membrane (S1), displacement norms (USUM), anchor loads and traction on border cables (Ncabos), for the X-wind load case.

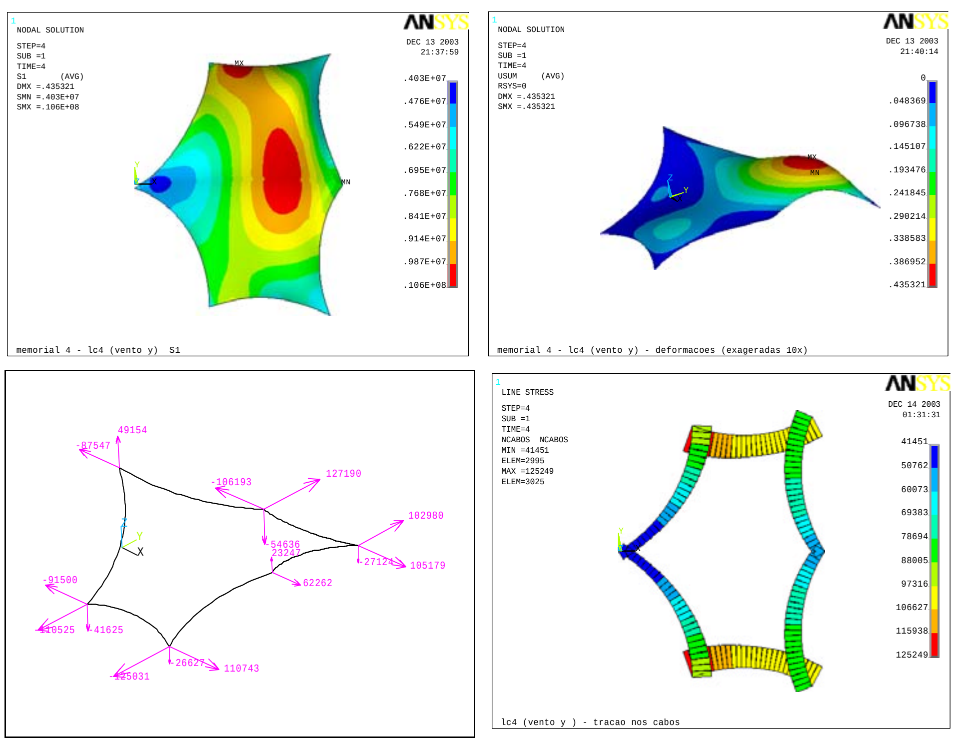

Figura 7. Maximum first principal stresses along the membrane (S1), displacement norms (USUM), anchor loads and traction on border cables (Ncabos), for the Y-wind load case.

PATTERNING

The geometry of the membrane, compatible with the prestressing loads, also served as departure point for the definition of the membrane's fabric patterns, that were determined, after a suitable definition of the seam lines, by a sequence of structural analyses (one for every fabric strip), dragging all the nodes of each strip to a convenient arbitrary plane, by means of imposed nodal displacement. The computational planification process was afterwards validated through a physical, reduced scale PVC fabric model, also employed for the definition of fabrication and assembling procedures.

Figura 8 shows the flat cutting patterns produced by means of the structural planification of the 3D strips show in figure 2. The patterns, generated with the aid of the ANSYS finite element code, were electronically transferred to '*Formatto Coberturas Especiais*', to proceed with detailing of seams, vertices and border cables, and subsequent fabrication. Besides trying to be aesthetically pleasant, the definition of the strips shown in Figure 3 sough the minimization of fabric waste, inherent to the process of lay-out of the patterns onto the fabric rolls. Figura 9 shows a quick test re-assembling of the flat patterns, printed in a single A4 sheet of paper. Figura10, by its turn, shows the 1:10 model, build by the membrane constructor, using a PVC coated, polyester fabric, in order to validate the computational process and to assist on the definition of the fabrication and assembling procedures.

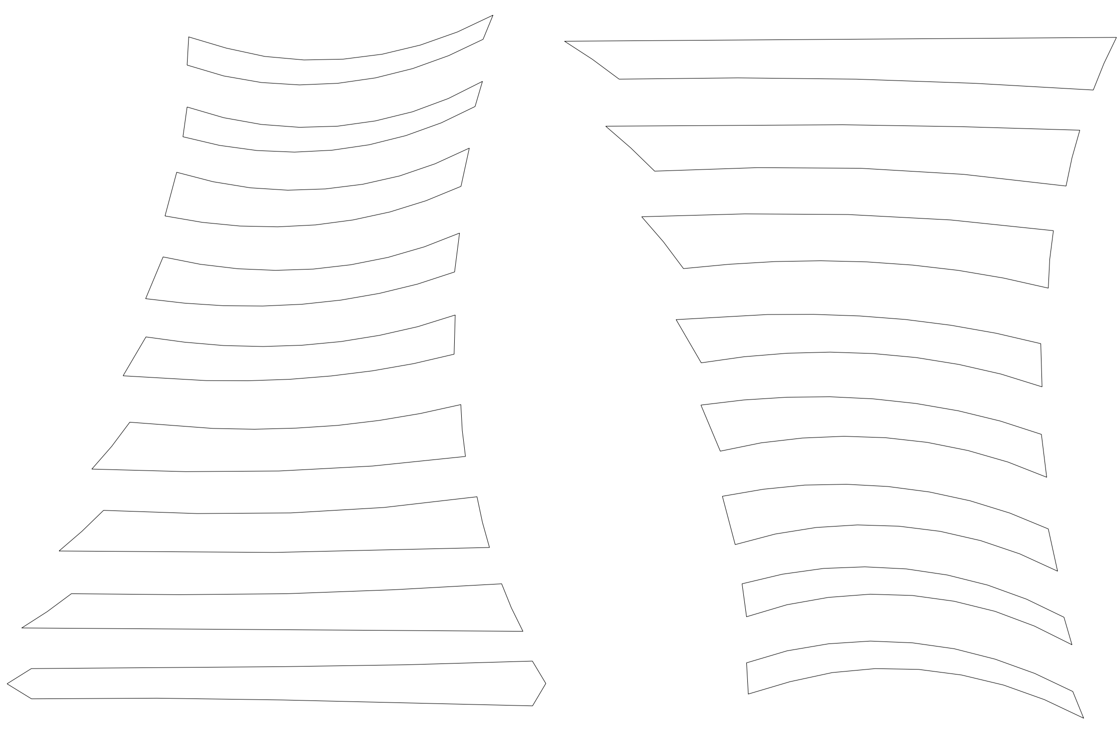

Figura 8. Cutting patterns for the membrane of the 'Memorial dos Povos de Belém do Pará'.

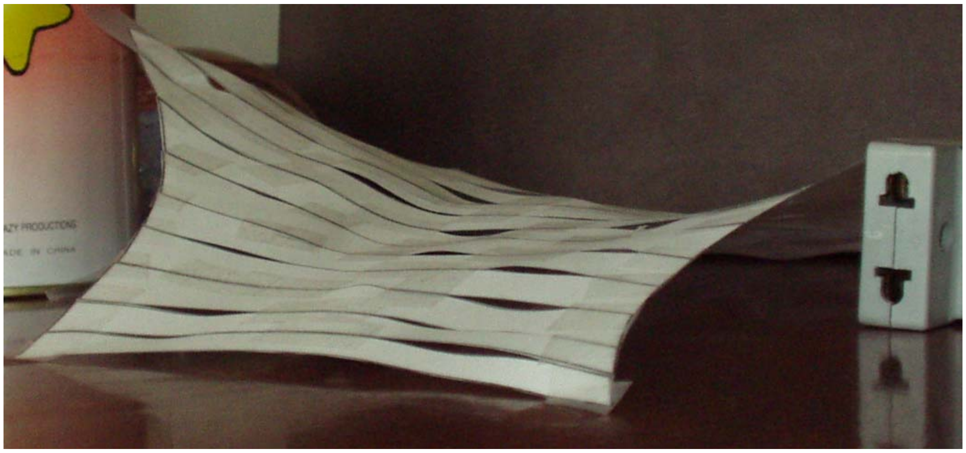

Figura 9. Assembling of a small scale, paper model, from flat patterns printed in an A4 sheet of paper.

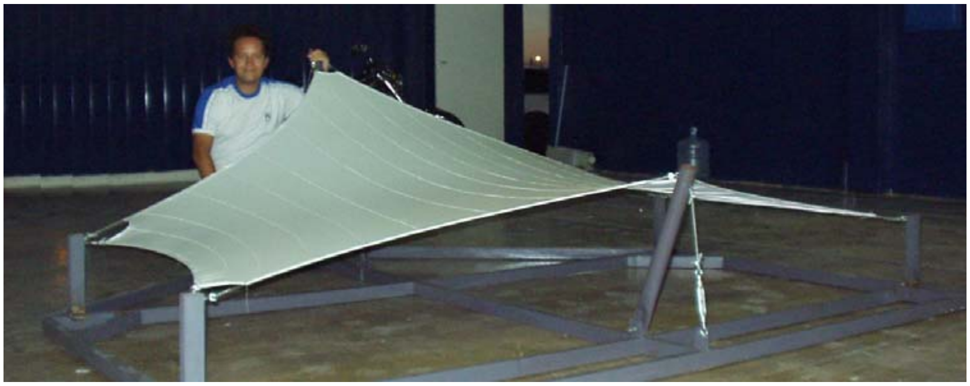

Figura 10. 1:10 scale fabric model of the membrane of the 'Memorial dos Povos de Belém do Pará'.

ASSEMBLING OF THE MEMBRANE ROOF OF THE MPBP

Assembling of the membrane roof of the roof of the MPBP was performed by *Formatto Coberturas Especiais*, during July, 14, 2004. Figure 11 shows three stages of the assembling process. Prestressing of the membrane was performed controlling the traction in the stays of the king and queen poles, by means of hydraulic actuators, as well as turnbuckles inserted at the border cables located between tripod anchors, which were stretched until all wrinkles in the membrane were removed (in Figure 11(c), some wrinkles close to the lateral vertices are still to be removed with the aid of the turnbuckles). Although the process does not guarantee imposition of the exact stress values, as calculated during the numerical analyses, the verification of complete absence of wrinkles, combined with the control of the loads on both membrane high vertices, was deemed precise enough, for practical purposes. Figure 12 shows the final set up of the structure, with the membrane completely taut. Figure 13 shows some details of the membrane and the anchorage system.

Figure 11. Three different stages of the assembling of the membrane roof of the MPBP.

Figure 12. Final set up of the membrane roof of the MPBP, with the membrane completely taut.

Figure 13. Some details of the MPBP membrane roof and anchorage system.

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