THE CUTTING PATTERN GENERATION OF THE PILGRIM'S TENTS FOR PHASE II OF THE MINA VALLEY PROJECT

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ABSTRACT

This paper deals with the design of a range of modular stressed textile structures for Phase II of the Mina valley tent city project in Saudi-Arabia. The technical problems, as well as the state-of-the-art computational solution strategies adopted are described.

INTRODUCTION

Amongst the most interesting of stressed textile projects in recent years has been the Mina valley project in Saudi Arabia. Every year two million followers of the Islamic faith make the Haj pilgrimage to the holy city of Mecca. As part of the event, these pilgrims travel to nearby mount Arafat where they spend the night camping in the Mina valley. Following a series of fatal disasters culminating in a large fire in 1997, the Saudi government decided to replace the existing cotton structures with fireproof teflon coated glass tents. Phase I of the project, which was carried out by Koch, SL and Tensys during 1997 and 1998, provided 25% of the planned 40,000 tents. Phase II was carried out by a completely different group with the membrane engineering provided by technet GmbH. Over 16,000 tents were built and installed during Phase II making this the world's largest lightweight structure project. The extent and relative locations of Phase I and Phase II are shown in Figure 1.

TECHNICAL REQUIREMENTS

As with Phase I, the majority of the tents were to be constructed from six modular designs. These rectilinear structures ranged in size from 4x4m through 8x6m, 8x8m, 8x9m, 8x10m to 8x12m. The general appearance of the tent forms needed to be similar to the original configurations. These were patterned from four triangular panels each of which was fabricated from cloth strips with the textile weft parallel to the outer boundaries. Since there were such a great number of tents to fabricate the issue of cloth wastage was paramount. The textile was procured in a very large number of different widths. Pattern sets were therefore needed for each of these widths and for each of the different roof configurations.

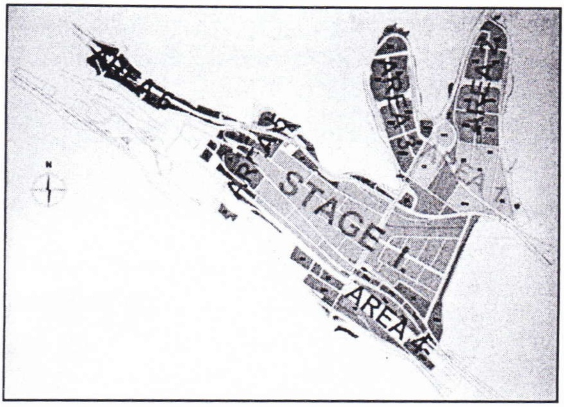

Figure 1 Map of site showing Phase I and Areas 1-6 of Phase II

FORM-FINDING AND LOAD ANALYSIS

Each of the designs were based on a similar configuration, namely a fixed rectangular boundary with a central mast. The membrane was suspended from boundary cables which were connected to the mast at four points. The initial conceptual form-finding was performed by the Jeddah engineering office TTT according to a constant stress basis. Constant stress surfaces generally perform poorly in conical high-point configurations. In this case the complete surface was divided into four constant stress panels spanning between the higher stiffness reinforced radial seams. Since the structures were not subject to particularly high applied load and have no snow load this was an acceptable design decision. An example of one of the TTT conceptual design forms is shown in Figure 2. Due to the irregularity of these meshes it was necessary to regenerate them using the formfinding module of **Easy**. An example of a production surface is shown in Figure 3.

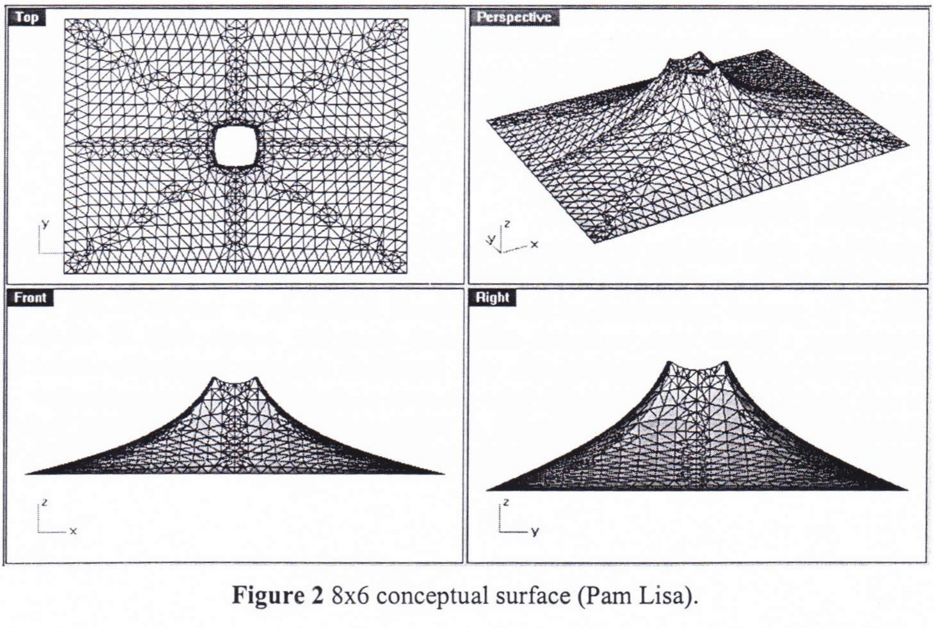

Figure 2 8x6 conceptual surface (Pam Lisa).

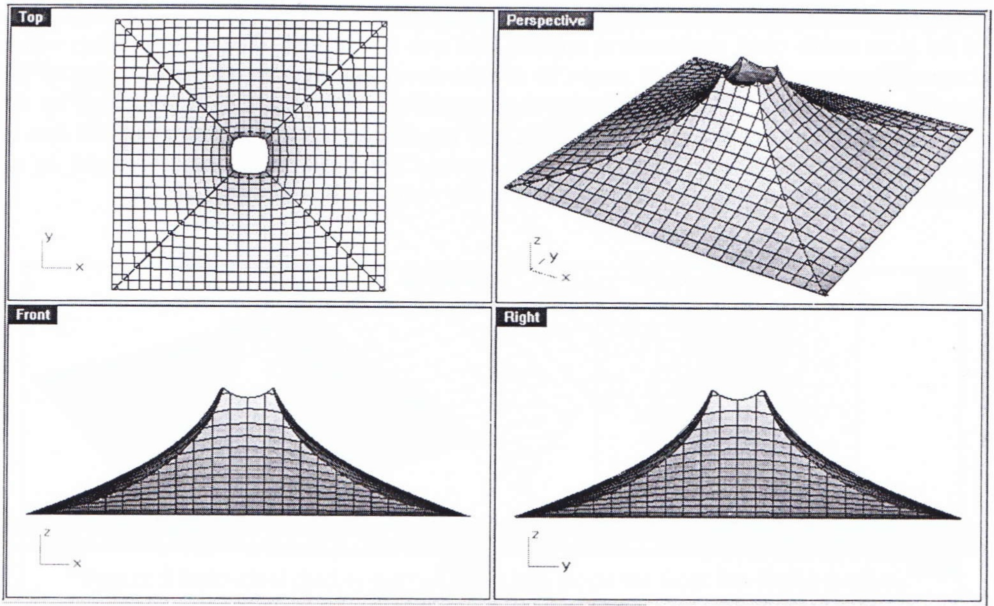

Figure 3 8x8 production form-found surface (Easy).

CUTTING PATTERN GENERATION

Although the overall sizes of the various tent designs are quite modest, the technical challenge of patterning the structures is of the highest level. It is a little known paradox of textile structure design that smaller structures are, in general, more difficult to pattern than larger ones. This is due to the fact that with larger structures the limitation of maximum fabric width necessitates the use of many cloths. The 3D to 2D patterning distortion is therefore relatively low for each cloth. With smaller structures the maximum fabric width is relatively large compared to the stuctures overall dimensions. Since cutting, preparing and welding each seam is expensive, it is inevitable that fabricators wish to use the minimum number of cloths in any application. Usually the higher distortion experienced by the relatively wider strips used in smaller structures is mitigated by the fact that lower stiffness membranes are used. In this case, however, the textile used was not only PTFE coated glass, but also a very heavy duty grade. With a completely non-adjustable fixed boundary, the pattern generation problem therefore becomes extremely sensitive.

For the Phase I roofs the cloths were oriented in the same way as the original cotton tents, namely with the weft parallel to the outer boundaries. This is good engineering practice when the roof is subject to high downward loads such as snow. The reason for this is that the seams do not experience the maximum fabric stress, and since the warp is stiffer less deflection will be experienced. The higher stiffness of the warp does however lead to problems for this configuration. In order to achieve the desired constant stress, the cloth compensation must be much higher in the weft direction. This means that the fabric needs to be strained more at the borders during installation than if the warp runs parallel to the frames. More serious is the very low strain range which is permissible in the fabric during vertical adjustment of the mast top. The practical result of this is that tents patterned according to the Phase I layout are fundamentally more susceptible to wrinkling than those patterned with the warp parallel to the frame boundaries. Since wrinkling was a major problem with the Phase I roofs it was decided to change the layout direction for Phase II. Due to the very high strength of the glass textile used, resistance to applied load was not critical. The only problem which computational analysis predicted might be of relevance was progressive ponding due to the flat lower areas associated with constant stress surfaces. This would be exacerbated by the lower stiffness in the tents radial directions. In practice a number of roofs did fail due to ponding under heavy rain. This occurred because the roofs were left overnight in an unstressed condition. When correctly tensioned the roofs performed as predicted.

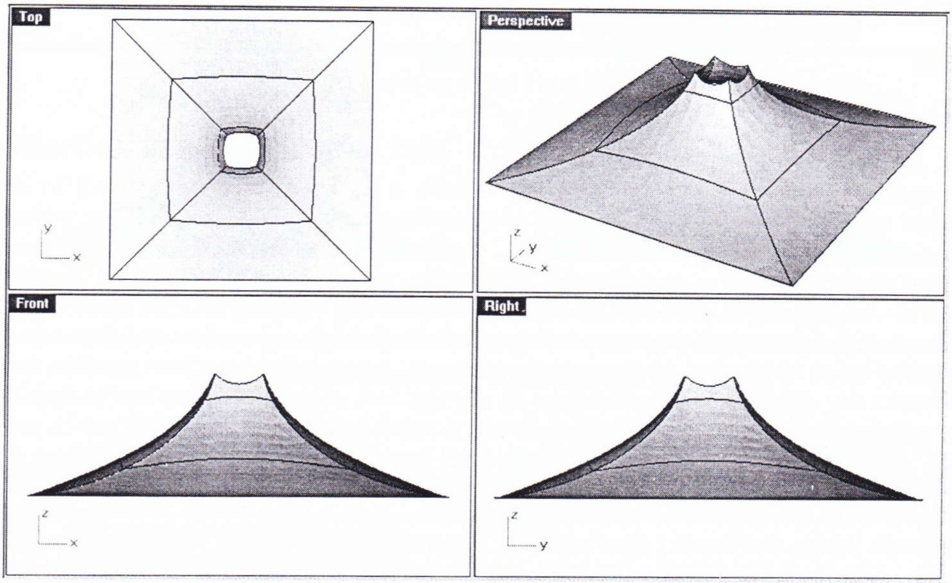

Figure 4 8x8 production surface showing seam layout.

The cutting pattern generation was performed using technet **EasyCut**. The first stage in the cutting pattern generation procedure was the generation of the geodesic lines. Figure 4 shows one of the seam layouts for the 8x8 roof. Figure 5 shows the result of cutting up the form-found surface according to these seam lines together with additional geodesic cloth centre lines. These half strips are still doubly curved and non-developable. Each sub-surface was then flattened to create planar boundaries. Within each a new regular surface was generated and then mapped back to the 3D space according to a local parametric coordinate system. These new surfaces were then perturbed using a sophisticated adjustment procedure which ensures developability while minimising deviation from the doubly curved sub-surfaces. The results from this are shown in Figure 6. These developable surfaces were then trimmed using cutting surfaces projected from the doubly curved cloth boundaries using the surface normals. The resulting planar half strips are shown in Figure 7. Since the adjacent seam lengths will necessarily now be different, the planar geometry must be adjusted again to ensure compatibility. After joining the half cloths together the patterns are shown in Figure 8. The final procedure to be performed was the cloth compensation and detailing.

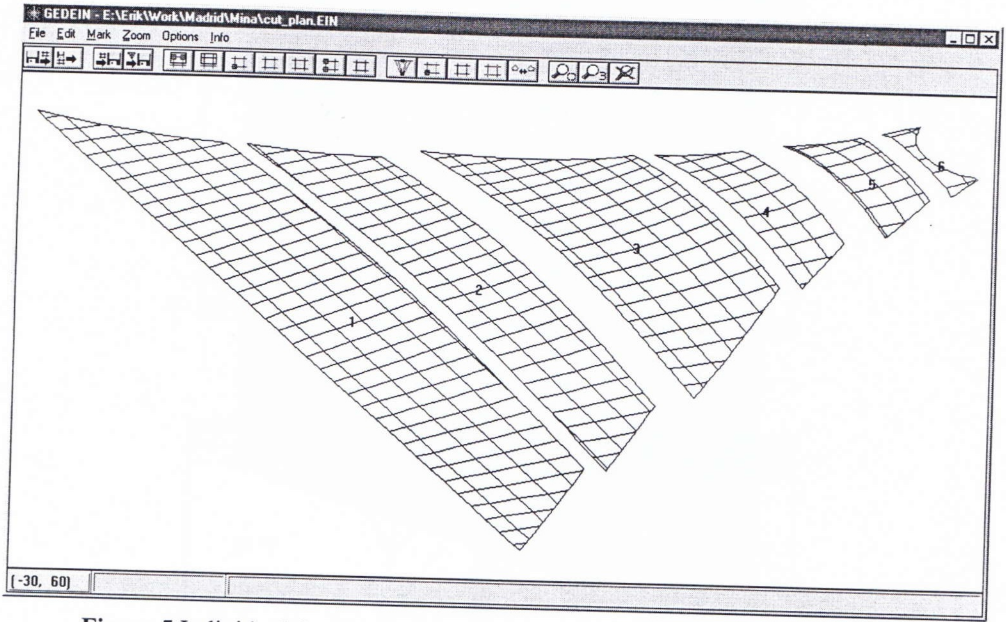

Figure 5 Individual doubly-curved half cloth strips cut from for-found surface.

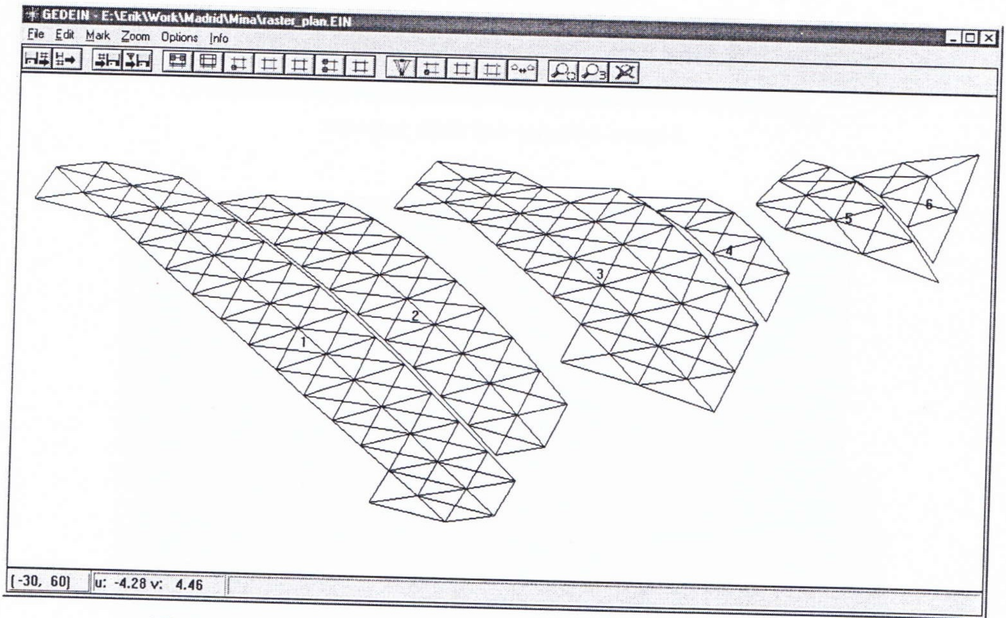

Figure 6 New developable half cloth strips grown over cut strips.

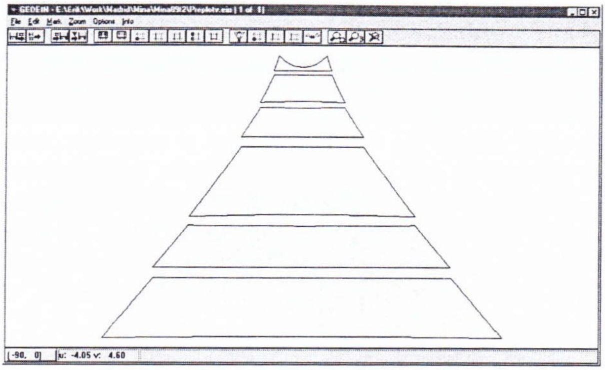

Figure 7 Planar half cloth patterns.

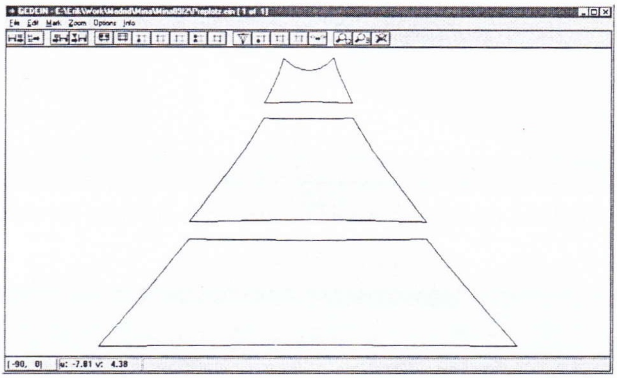

Figure 8 Planar full cloth patterns.

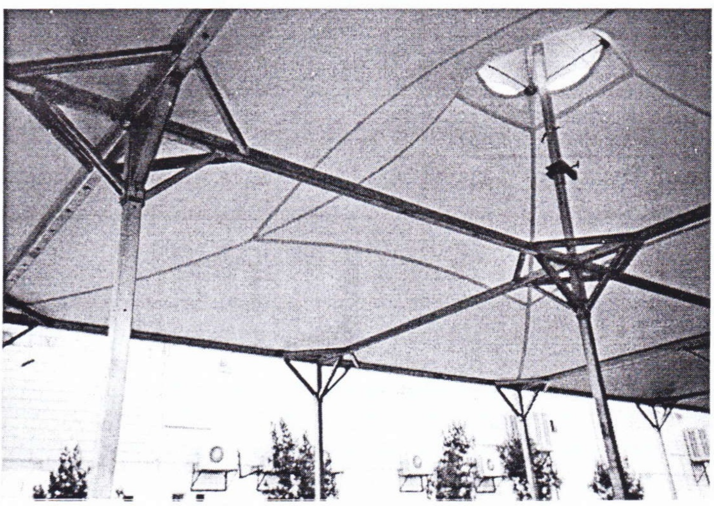

Figure 9 Interior view of prototype

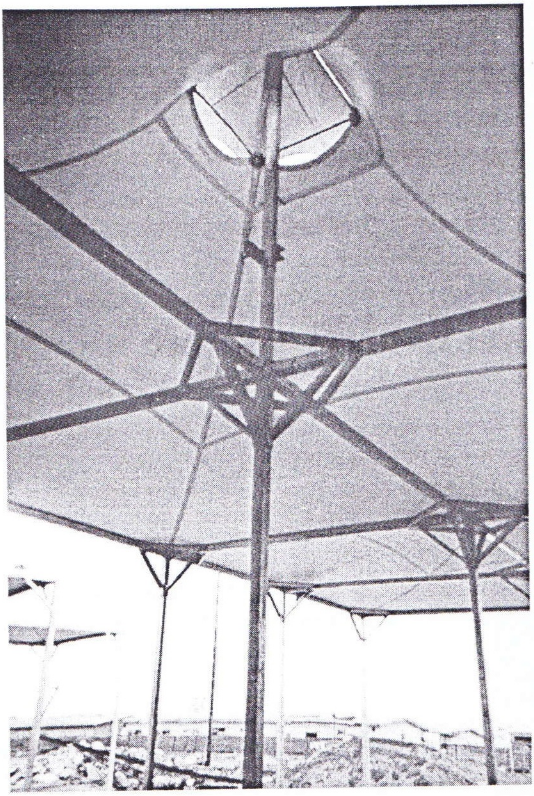

Figure 10 Interior view of prototype.

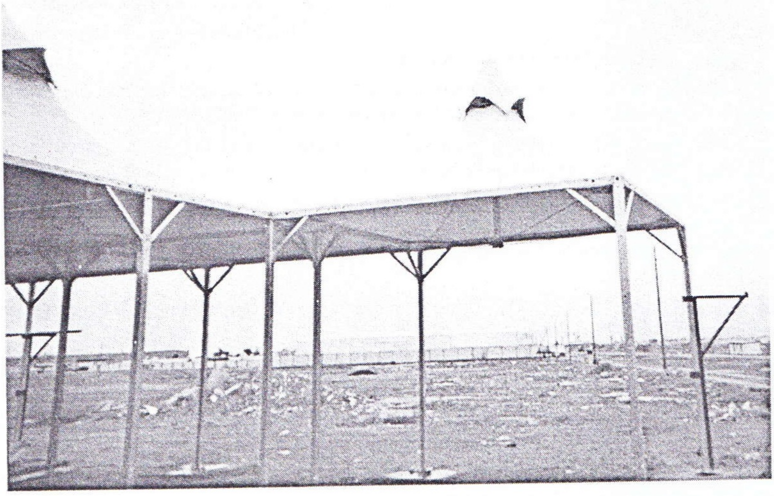

Figure 11 Exterior view of 4x4 prototype.

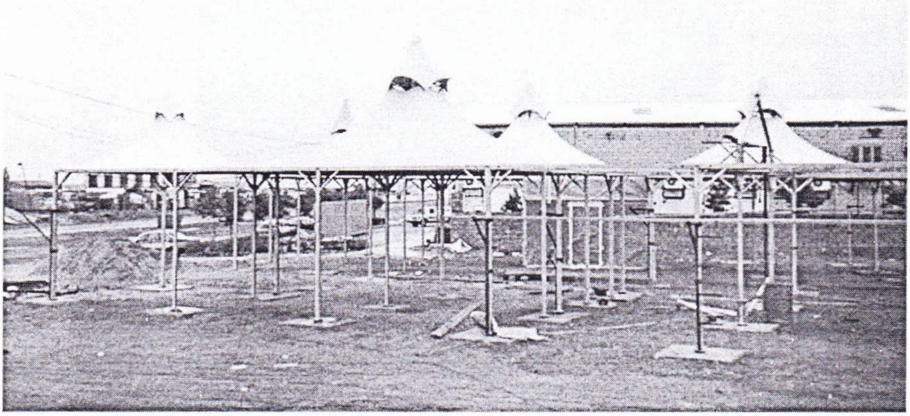

Figure 12 Exterior view of prototypes.

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REFERENCES

[1] Gründig, L., (1975), `Die Berechnung von vorgespannten Seilnetzen und Hängenetzen unter Berücksichtigung ihrer topologischen und physikalischen Eigenschaften und der Ausgleichungsrechnung,' Dissertation am IAGB, Universität Stuttgart, DGK Reihe C, Nr. 216, 1976 and SFB 64-Mitteilungen 34/1976.

[2] Gründig, L. and Bahndorf, J., (1988), `The Design of Wide-Span Roof Structures Using Micro-Computers,' *Computers & Structures* **30**, 495-501.

[3] Gründig, L. and Bäuerle, J., (1990), `Automated Cutting Pattern Determination and Control for Prestressed Membranes,' *Proceedings of Textile Composites in Building Construction*, Part 2, Pluralis, Lyon, 1990.

[4] Gründig, L. and Bäuerle, J., (1992), `Cutting Pattern of Structural Membranes - Precise Physical Modelling,' *Proceedings of the IASS- Symposium*, Toronto 1992

[5] Gründig, L. and Moncrieff, E., (1993), `Formfinding of Textile Structures,' in *Proc. Studiedag-Seminaire Textielstrukturen Architecture Textile*, Vrije Universiteit Brussel, 25th May 1993.

[6] Gründig, L. and Moncrieff, E., (1993), `Cutting Pattern Generation of Textile Structures,' in *Proc. Studiedag-Seminaire Textielstrukturen Architecture Textile*, Vrije Universiteit Brussel, 25th May 1993.

[7] Gründig, L. and Moncrieff, E., (1995), `On the Optimal Layout of Cutting Patterns for Architectural Textile Structures,' in Obrebski, Jan B. (Ed.), *Lightweight Structures in Civil Engineering* Proceedings of the International Conference on Lightweight Structures in Civil Engineering, 25-29th September 1995, Warsaw, Poland.

[8] Linkwitz, K. and Schek, H.-J., (1971), `Einige Bemerkungen zur Berechnung von vorgespannten Seilnetzkonstruktionen,' *Ingenieur-Archiv* **40**, 145-158.

[9] Moncrieff, E. and Topping, B. H. V., (1990), `Computer Methods for the Generation of Membrane Cutting Patterns,' *Computers and Structures* **37**, 4, 441-450.

[10] Schek, H.-J., (1974), `The force density method for form finding and computation of general networks,' *Computer Methods in Applied Mechanics and Engineering* **3**, 115-134.

[11] technet GmbH, (1999), *Easy, User manual for integrated surface structure design software*, technet GmbH, Maassenstr. 14, D-10777 Berlin, Germany.