Systems for Lightweight Structure Design: the *State-of-the-Art* and Current Developments

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Summary. *This paper deals with the design of lightweight structures. In particular the role of computational modelling software in this process is discussed. The state-of-the-art is first described paying close attention to the requirements for industrially effective solutions. Some of the less well understood aspects of the modelling processes are discussed. In particular the load analysis, form-finding and cutting pattern generation processes are covered. The modelling of textile is addressed in detail. Approaches to the design of software design systems for lightweight structure design are discussed in the context of system flexibility and effectiveness. Finally, interesting applications in the field of lightweight structures arising from design system developments are highlighted.*

Key words: design, lightweight structure, modelling, simulation, textile, element type, form-finding, geometrically non-linear structural analysis, elastically non-linear structural analysis, cutting pattern generation, crimp, pneumatic structure, hybrid structure, adaptive design

1 Introduction

To most structural engineers and architects the design of lightweight structures is mysterious. The objective of this paper is to summarise the *state-of-the-art* in lightweight structure design systems in order to highlight several important concepts. Emphasis is directed to the requirements of industrial procedures.

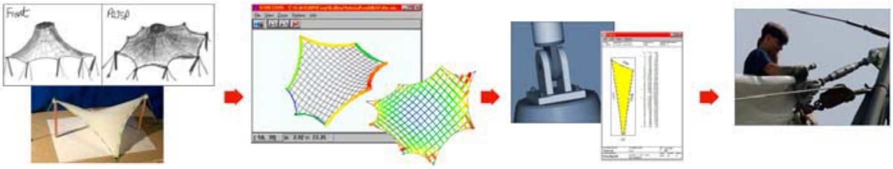
2 Lightweight Structure Design

2.1 Design Process

As with conventional structural engineering projects, the design process for lightweight structures involves three key players. These are the *Client*, the *Architect* and the

E. Oñate and B. Kröplin (eds.), Textile Composites and Inflatable Structures, 17–28.

Structural Engineer. The client commissions the project and invites tenders from architects. The architects prepare conceptual designs working in collaboration with structural engineers. The client chooses a conceptual design and appoints the architect. The architect, again working in close collaboration with a structural engineer proceeds to refine the conceptual design into a production design. Finally the design is fabricated and installed. The critical path of this design process is shown in Fig. 1. In reality there are several design modification cycles operating.



Conceptual design Form-finding/ Load analysis Patterning/ Detailing Installation

Fig. 1. The phases of the design process critical path

2.2 Design deliverables

The deliverables can be conveniently divided between those for the conceptual and production designs.

Conceptual design

• Pre-stress surface geometry	***Form − finding***
• Reaction, support and cable forces	***Load Analysis***
• Textile stresses	

Production design

• Pre-stress surface geometry	***Form − finding***
• Reaction, support and cable forces	***Load Analysis***
• Textile stresses	
• Cloth pattern system line geometry	***Cutting Pattern Generation***
• Support structure design	***Detailing***
• Cable dimensions	
• Connection design	
• Cloth and reinforcement cutting patterns	

Detailing is a critical process and highly integrated with the other processes. It will, however be the *Form-finding, Load Analysis* and *Cutting Pattern Generation* processes which will be mainly considered here.

2.3 Load Analysis and Form-Finding

The tasks

Load analysis and form-finding require the determination of Force Equilibrant models. In a *Force Equilibrant* model the residual forces acting on any degree of freedom after summing the internal and external loads acting there is zero. In the case of computational load analysis the elemental forces may be calculated using several elastic models. Similarly several methods may be used to define the elemental forces in computational form-finding. The load intensity distribution must be estimated.

Historical development
Before the development of computational structural modelling, textile structures were form-found using physical models and load analysis was performed using hand calculations. The development of linear structural analysis software had little applicability for the design of textile roofs due to their strong geometrical non-linearity Non-linear systems have been developed since the 1970's and are now routinely used.

Current system configurations
Today industrial systems are broadly based on three main solver algorithms.

- *Conjugate Gradient (CG)/Force Density (FD)*
- *Dynamic Relaxation (DR)*
- *Modified Stiffness (MS)*

Developments in mainland Europe have mostly used *CG/FD* solvers, Britain has concentrated on *DR*, and Japan and the USA have mainly used the *MS* method.

Two element types are commonly used to model textile roofs. Cable net models using link elements have been popular in *CG/FD* systems, while triangular continuum elements have been typically used in *DR* and *MS* systems. It is important to highlight that the prevalence of using particular elements with particular solver algorithms does not have a theoretical or computational basis. *CG/FD* systems with triangular continuum elements are used when appropriate, and *MS* and *DR* systems can also use link elements to model textile. Appropriate element types for the modelling of lightweight structures will be discussed in Section 3.2 below.

2.4 Cutting Pattern Generation

The tasks
Cutting Pattern Generation is the process where two dimensional unstressed cloth polygons are created from three-dimensional doubly curved stressed surfaces. This involves the specification of seam line locations, transformation of the stressed 3D surfaces to stressed 2D surfaces, and compensating the stressed 2D surfaces to unstressed 2D surfaces.

Historical development
Before the advent of computer modelling, textile roofs were patterned using physical models. Simple triangle strip development between computer model seam lines were next implemented and have been used successfully for medium to large structures. Distortion minimisation techniques have been adapted from map making to cope with the demands of smaller and more sensitive configurations.

Seam generation
Regardless of whether physical or computational modelling is used, patterning based on geodesic seam lines is the preferred approach. This is because geodesic lines

are, by definition, straight when developed to a plane. Cloths patterned between geodesic seam lines will therefore be straighter than non-geodesic patterns. Non-geodesic patterns typically have banana or "S" shaped cloths which cause larger cloth wastage.

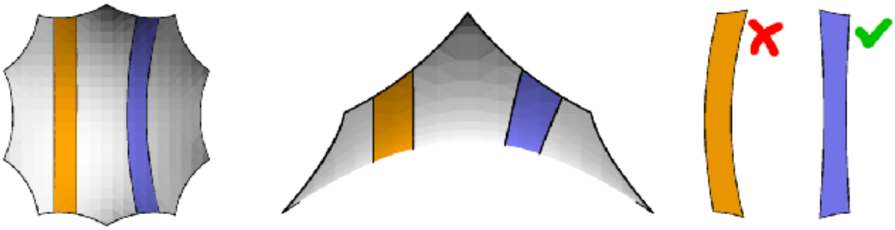


Fig. 2. Non-geodesic (lighter cloth), and geodesic (darker cloth) patterns

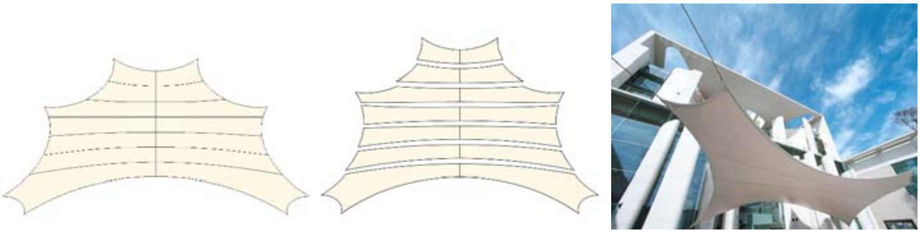


Fig. 3. Architecturally mandated semi-geodesic seam pattern for the German Chancellory

In some situations architectural requirements mandate non-geodesic seam lines. A prominent example of such a situation is the *German Chancellory* [1]. In such situations the use of line generation algorithms which are curvature based rather than length-minimising is helpful [2].

Cloth planarisation

The process of transforming a doubly curved surface into planar cloth sub-surfaces requires the introduction of distortion. The most basic approach taken to solve this problem is to define the cloths in terms of developable triangle strips. This works entirely adequately for large structures, but small structures are more difficult because cloth roll width does not limit pattern widths. This results in a wish to have fewer cloths for economic reasons. Meshes for small structures based on simple triangle development fail to reliably model the surface [3]. This can be seen in Figure 4. In such cases the use of more sophisticated distortion minimisation algorithms is very effective.

Fig. 4. Planarisation: (a) Large structure simple triangle development, (b) Small structure triangle development, (c) Small structure deformation minimising flattening

2.5 Design Methodologies

Textile structures have been designed in three general ways.

Non-computational: Physical models are used to form-find the pre-stress surface geometry and create the cutting patterns. Simplified "hand calculations" are used to predict structural response.

Non-specialised software: Non-equilibrium computational modelling software, such as *3ds max*, is used to generate the pre-stress surface geometry and cutting pattern generation. Standard FE structural analysis software is used to perform load analysis.

Specialised software: Lightweight structure task-specific equilibrium based computational modelling software is used to perform form-finding, load analysis and cutting pattern generation.

The non-computational method has the advantages that it is intuitive, the form can be realised, it can be implemented with low initial investment, and modification of conceptual forms is quick and simple. It suffers from its lack of computational non-linear structural analysis, low precision and lack of computational mesh for rendering. Its slowness, particularly with respect to making modifications to the production form and cutting patterns, makes it operationally expensive.

Using the non-specialised software method leverages existing CAD and analysis software skills and provides many sophisticated geometric tools. With few exceptions, the forms generated are, however, not force equilibrant. Consequently they can not necessarily be realised with a tensile surface. Lack of integration between the mesh generation and analysis leads to slow design modification cycles. Conventional FE software is often inappropriate for use with textile models. In particular, convergence problems are usually experienced by standard FE systems when dealing with textile slackening on-off non-linearity.

Specialist textile structure software systems quickly provides high confidence, high precision, integrated solutions. Initial investment is higher but when design volume is adequate, per-design costs are low. It is therefore the recommended method for production design. Having said that it is important to stress that the continued use of physical modelling during the conceptual modelling phase should always be encouraged.

3 Modelling Textile

The materials most commonly used for lightweight structures are PVC coated polyester and PTFE coated glass. Despite different production methods these textiles are similar in their structural configuration. A woven base cloth is coated on both sides as shown in Fig. 5. The warp threads are typically less crimped than the weft. The warp and weft crimp are more similar with *Precontraint* textile due to the weft stressing during coating. All textiles exhibit extremely complex structural behaviour. In addition to pronounced bi-axial non-linearity, they have thermally and load history dependent relaxation. Consequently they are very difficult to model.

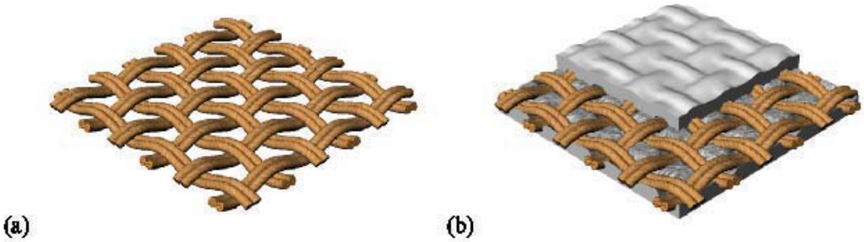


Fig. 5. Schematics of coated textile composition. (a) Base cloth. (b) Base cloth with coating

Elastic modelling is needed for both “what if ...” prediction and production dimensioning. The relative difficulty of these processes is radically different with lightweight compared to conventional structures. Lightweight structures are inherently safer structures but are more susceptible to aesthetic failure due to patterning errors.

3.1 Modelling and Simulation

It is helpful to consider the terms *Modelling and Simulation.* In common usage these terms are relatively synonymous. In the field of structural engineering design I endorse the following distinction.

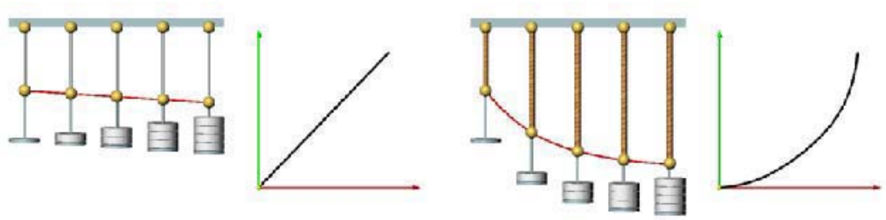
- *Structural Modelling* is the general use of a structural model to predict a structural response to a loading condition.
- *Structural Simulation* is Structural Modelling using calibrated models.

Models have different levels of complexity, as well as different levels of accuracy. It is important to recognise that models must be appropriate to the task they are being used for. There is no “best” model for all situations. Many people concentrate on absolute levels of model complexity. There is no doubt that the highest levels of model predictive accuracy will usually be achieved with a model of high complexity. Such accuracy will, however, require extensive quality calibration. Without such calibration the extra sophistication of the model becomes a liability. Some people express the view that a model is only as good as its accuracy. My opinion is that a model is only as good as its relevance to what it is being used to model.

It is a remarkable fact that so little measurement of lightweight structures has been conducted. In particular almost no textile surface measurements have been performed. We advocate the use of non-contact photogrammetry for strain measurement of in-situ textile structures [4].

3.2 Element Types for Textile Modeling

Before considering the problem of modelling elastically non-linear textile, consider the modelling of simple 1 DOF ties. Fig. 6 shows the load deflection behaviour for a steel bar and a low stiffness rope. These illustrate elastically linear and elastically non-linear behaviour respectively. In practice with both linear and non-linear ties stiffness values for load analysis are typically linearised according to narrow bracketing based on the expected and model observed strain. Cable compensation needs to consider in detail the hysteretic relaxation behaviour.



Steel tie **Low stiffness rope**

Fig. 6. DOF elastically linear and elastically non-linear ties

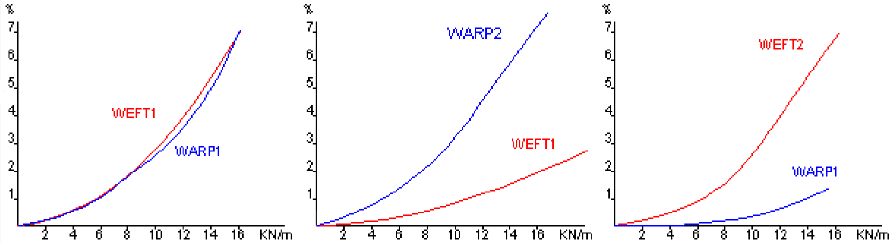


Fig. 7. Stiffness relationships of coated textile (Ferrari [5] *Precontraint* 502)

Modelling textile is much more complicated. Sanitised stiffness relationships from biaxial stress tests are shown in Fig. 7. Typically such graphs are generated for both the warp and weft directions under several fixed warp to weft stress ratios. These are often 1:1, 2:1, 1:2, 1:0 and 0:1. Clearly such tests typically provide extremely small sample sets.

Due to the nature of the weaving process the warp and weft threads are crimped and interact in a complex way. Various composite crimp models have been developed which seek to model the micro structure of the textile within the coating matrix. Crimp models, when properly calibrated, can achieve very high accuracy. As such these models are the most suitable for applications where design duration and cost is secondary to the performance of the structure. Satellite and other space structures are examples. In the architectural textile structure industry, complex crimp models suffer from slow performance and the infeasibility of adequate calibration.

As stated earlier, two element types are mostly used in industrial lightweight structure design systems. These are the cable net (link) and continuum (usually triangulated) models. There is a controversy concerning the relative accuracy and appropriateness of these models. Both elements are used in our systems, as well as several others. We advocate the cable net model as being the most appropriate for current industrial practice on the following basis.

The shear resistance of textile is extremely low and is customarily ignored by everyone. *Poisson*'s ratio effects caused by the textile structure are usually small, but can be noticeable in some parts of some structures. Contrary to extensive belief the cable net model can, like the continuum model, be used to model this effect. It must be stressed, however, that for both methods the sophistication is primitive and limited by the difficulty in choosing *Poisson*'s ratio values. Looking back to the biaxial test data in Fig. 7 above it should be clear that the extraction of a single representative *Poisson*'s ratio parameter is pure fantasy. Another element type which we have developed for textile structure modelling is cruciform based with link forces a function of the two cruciform link strains. We believe that in the medium future the use of automatically calibrated cruciform elements will become feasible. This will require the development of an integrated system linking the producers, test laboratories, software developers and design engineers. The fundamental test will be whether it is possible to use an automatically calibrated model to confidently predict any real biaxial test.

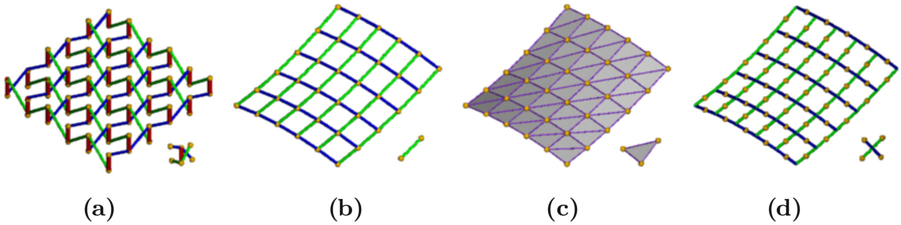


Fig. 8. Element types: (a) Composite crimp, (b) Cable net link, (c) Continuum triangle and (d) Cruciform

It is important to stress again that extra complexity does not necessarily imply extra accuracy. In particular, complex models require many difficult to measure parameters. Which are usually unavailable. When parameters are unavailable, less complex models are no less accurate and maintain contact between the designer and the physical behaviour.

4 Design System Architecture

4.1 Design Sensitivity

Structural configurations vary in their vulnerability to design, fabrication and installation errors. Some configurations are very tolerant and can be successfully installed with large pattern design flaws or installation errors. Other configurations are so sensitive that design and production tolerances have to be extremely narrow. To the novice designer it is not obvious whether a configuration is sensitive or tolerant. Contrast the simple saddles and the *Mina* [6] roof structures shown in Fig. 9.

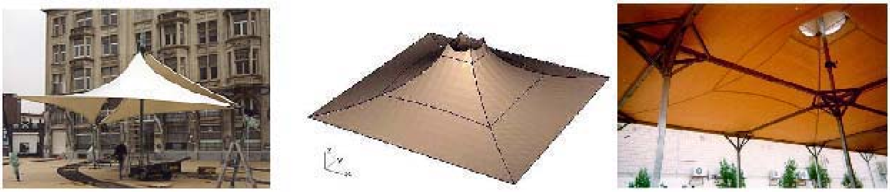


Fig. 9. (a) Tolerant tensile border saddle configuration. (b,c) Sensitive *Mina* valley tent

With the simple saddles we have maximum adjustability. Errors in the compensation of the patterns would mean that the installed system line geometry will differ significantly from the computer model. Such an outcome will usually still be completely acceptable. With the *Mina* roofs we have one of the most sensitive configurations possible. There is a single adjustable DOF, the mast top height. We also have the additional difficulties of a very high stiffness PTFE coated glass textile, and the production constraint requiring very few cloths. Despite the apparent large unit volume of the project, the need for roll optimised patterning meant pattern refinement using scale 1:1 prototypes could not be effective. The *Mina* requirements were clear and therefore had to be accommodated. In many cases, however, avoidably sensitive configurations are regularly designed. The use of parametric search strategies is extremely useful for determining the sensitivity of particular structural configurations.

4.2 System Objectives

Due to the variability of lightweight structure configurations, the use of configurable self-contained tools is a sound basic philosophy. Each of the design modification cycles appropriate to the specifics of the project can be automated. The provision of multiple levels of design abstraction also leads to enhancements of both design quality and productivity. Higher level design parameters, such as boundary sags or textile pre-stress ratios, should be used as much as possible during the design modification cycles. Consider the examples of mesh fineness and mesh boundary sag variation shown in Fig. 10.

Full access to lower level parameters, such as link lengths, should be provided for maximum power. Such low level power functionality should be provided before high level optimisations are introduced. It is also worth highlighting that we favour streamlining the critical design iteration paths before performing such productivity optimizations to "once only" tasks.

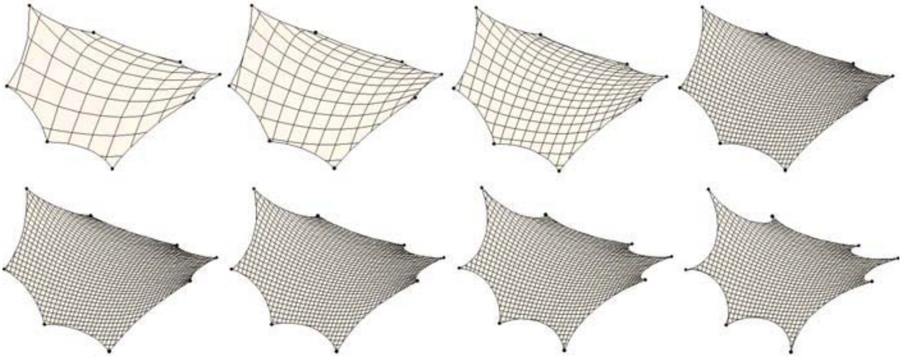


Fig. 10. Advantages of high-level mesh fineness and mesh border parameter variation

5 Current Developments

Dramatic developments are being made to computational design systems. In addition to enhancements in the power of the fundamental tools, emphasis is being focused on task based control interfaces, post-processing detailing and reporting. These system developments are enabling the feasible industrial exploitation of hitherto overly complex hybrid configurations. By integrating sophisticated technology for "as built" geometry feedback in *Adaptive Design* systems, installation accuracy and confidence can be greatly enhanced.

5.1 Complex Hybrid Structure Designs

One of the most interesting developments in lightweight structure design is the increasing use of constant volume pneumatics and flexible battens for primary and secondary load bearing or stiffening. *Tensegrity* structural configurations are also increasing in popularity. The use of active structural systems offers perhaps the most exciting prospects. Active control have been implemented with simple airhalls for many years at a very primitive level. The *Festo Airtecture* [7] developments extended the scope of pneumatically stressed structures significantly. Current developments include much more adventurous configurations, especially those for automatic deployability and even fully autonomous mobility. The actively controlled *Baba Yaga* walking shelter, which brings together many of these concepts, is shown in Fig. 11.

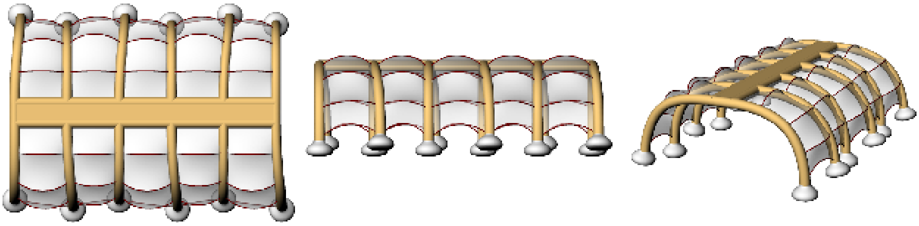


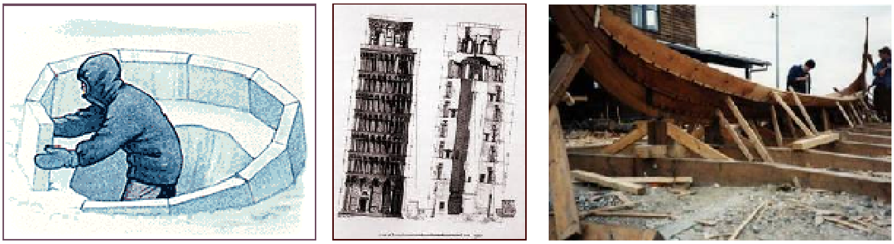
Fig. 11. Baba Yaga pneumatic mobile shelter during walk cycle

5.2 Adaptive Design

Lightweight structures are characterised by their complex doubly curved geometry. Designs are consequently usually composed of many precisely dimensioned components. Achieving an adequate level of installation success can therefore become difficult. With the increased use of CNC CAM more and more adventurous designs are being realised.

In conventional civil engineering CAD practice, design dimensions are mostly defined in absolute terms. Contractors produce structures which are within defined tolerances of these absolute values. Under such a system the "as built" geometry measurement serves only a policing role. If the measurement of "as built" geometry is progressively, and automatically, monitored during installation, the contractor is provided with valuable early warning of installation problems. Moreover, if the feedback geometry is integrated into the core design system, the geometry and location of the remaining components can be adjusted to match those already installed. This shift in paradigm brings the advantages of traditional highly skilled craft based construction methodologies to CAD/CAM.

An excellent traditional example of an *Adaptive Design* strategy is the construction of an igloo. Each of the ice blocks used is cut to fit the existing structure with high precision. Other pertinent examples from history are the leaning tower of Pisa and the building of wooden boats.



(a) Igloo construction. (b) Tower of Pisa. (c) Wooden boat.

Fig. 12. Traditional examples of adaptive design

Developments in close range photogrammetry and machine vision are now on the verge of providing the necessary automated real-time geometry aquisition systems to enable practical adaptive design systems. These systems look likely to prove very effective in all fields of complex geometric object design. The design of multi-cellular pneumatic structures is clearly of direct applicability.

References

1. TensiNet (2002) German Federal Chancellory. TensiNews 2:4, www.tensinet.com
2. Gründig L, Ekert L and Moncrieff E (1996) Geodesic and Semi-Geodesic Line Algorithms for Cutting Pattern Generation of Architectural Textile Structures. in T.T. Lan (Ed.), Proc. ASIA-PACIFIC Conference on Shell and Spatial Structures, Beijing
3. Moncrieff E and Topping BHV (1990) Computer Methods for the Generation of Membrane Cutting Patterns. Computers and Structures 37(4):441–450
4. Gründig L, Moncrieff E and Schewe H (1995) On the feasibility of using large scale photogrammetry to accurately determine in service strain distribution across three-dimensional textile roofs. 311-326 in W.D. De Wilde and P. Hamelin (Eds.), Euromech 334 Textile Composites and Textile Structures, Lyon
5. Ferrari Textiles (2003). www.ferrari-textiles.com
6. Moncrieff E (2003) Extreme Patterning: Lessons from the cutting pattern generation of the Mina valley tent city and the German federal chancellery projects. in M. Mollaert (Ed.), Designing Tensile Architecture: Proc. TensiNet Symposium, Vrije Universiteit Brussel, September 19th and 20th 2003, Brussels
7. Festo AG (2003). www.festo.com