Numerical Modelling in Tension Structure Design and Construction

D S Wakefield BSc PhD CEng MIStructE

Tensys Limited
16 George Street Bath BA1 2EN UK
Tel +44 1225 445600 Fax +44 1225 469001
Email d.wakefield@tensys.co.uk

1. Introduction

Recent years have seen rapid growth in the field of tensile architecture. There is now a well established base of projects ranging from simple free standing canopies to complex forms tightly integrated into a complete building construction.

Traditional applications such as EXPO pavilions and covered stadia have been joined by use as atrium walls for high rise buildings, the Chicago Beach Development in Dubai, and roofing for modern amenity facilities as focal points for prestige commercial developments, the SAGA and Inland Revenue projects in the UK [1].

Chicago Beach Tower Hotel

The use of modern materials, design methods and fabrication technologies have returned also to the basic provision of shelter. The rebuilding of the Pilgrims Accommodation in the Mina Valley for the annual Hajj in Mecca is currently entering the second of the project's three years. A total of 2.5million square metres of roofing will be installed, with additional walling within the modular building system.

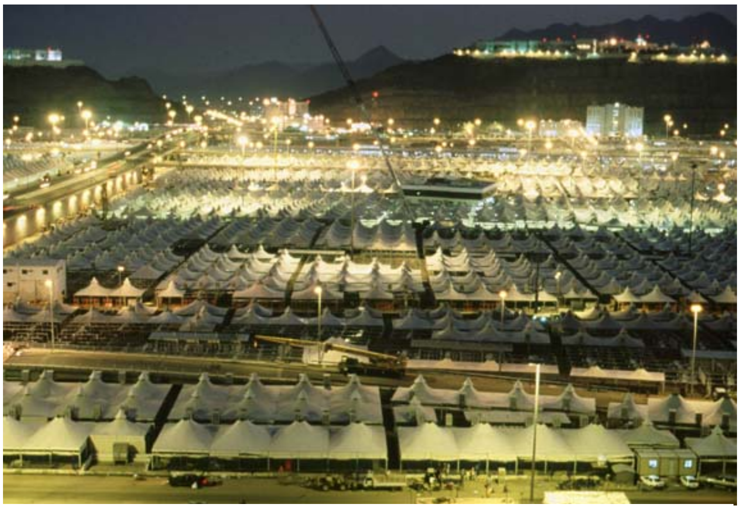
Structural membrane is employed as a building material for its ability to satisfy exciting aesthetic dreams, its combination of strength and lightweight in order to provide large clear spans, its possibilities to provide controlled levels of lighting and its adaptability to provide both portable and retractable solutions as well as static. The expansion in applications is shadowed by expansion in the range of materials. New coatings on PVC/Polyester fabrics are providing alternatives to PTFE/glass membrane. The development of materials with both strength and translucency sufficient to grow natural grass beneath is motivated by the commercial needs of covered sports stadia.

Engineering design capabilities have also grown in line with the applications. In particular numerical modelling, together with available computer hardware, has advanced so as to support the design process without placing any undue limitations upon it. There still remains, however, a high level of technical knowledge and experience necessary for the successful realisation of these projects in which form, structural performance, material specification and fabrication and installation skills are more closely interrelated than in any other building method.

2. Integration of Membrane Engineering into the Design Process

Membrane Engineering is the general term given to the specialist engineering services required for the design and construction of stressed membrane tensile structures. In particular it covers the numerical procedures for the formfinding, load analysis and patterning of these non-linear structures.

The necessary technical support may be supplied by a specialist membrane engineer who will integrate into the particular project design and construction team. The most successful tension structure projects are founded upon a close interaction between architect, structural engineer, membrane engineer and specialist contractor as a design is progressively refined and optimised from initial conception through to the construction phase. Even when such a close interaction is not possible, the membrane engineer can provide a chain of experience linking the various stages of a project because of his knowledge of the whole process.



Pilgrims Accommodation Project Saudi Arabia

It is not being suggested that the engineering of tensile structures is particularly difficult. It is, however, sufficiently different from conventional structures to require specialist treatment. Unlike steel or concrete building elements which resist loads in bending, all tension structure forces are carried within the surface, either by membrane stress or cable tension. The detailed shape of that doubly curved surface is critical to its engineering performance. It governs the magnitude of stresses and the amounts of deflection under load. The architectural possibilities of the shape are also constrained by the need to establish a form that is in physical equilibrium. In practical terms this means that there will be no areas of wrinkled fabric or slack cables in the completed structure.

This interrelationship between form and stress leads to the characteristic natural surface forms associated with tension structures. It also requires close co-operation between engineer and architect from the outset of a project in establishing a viable form. Although physical modelling may well be used at the start, sophisticated computer based analysis procedures are necessary for form refinement and investigation. These numerical techniques for form-finding are not readily available in general commercial analysis software packages.

Computer calculation of stress under wind and snow environmental loading is based upon a conventional finite element idealisation. This has to be modified to include the non-linear effects of the relatively large deflections of the structure under load, together with material non-linearities and the inability of cable and membrane components to compression forces. The software must also be integrated into the equilibrium form generation process.

On completion of the design, the computer model is also used to generate fabrication information in a form ready for shop floor use. This includes membrane cutting patterns, cable-net schedules and support structure component geometry. Tension structures are a high precision pre-fabricated item, and accurate geometric processing and fabrication is essential. It is generally not possible to correct errors on site.

Prior to final installation, computer analysis of the erection sequence may also be required. This can assess both structure loads during installation and the temporary forces imposed upon the support system. It may also be used to check on the stability of the structure when subject to applied wind or snow loading when only partially installed.

3. Available Numerical Solutions

As outlined above, the basic computational phases for membrane engineering are those of form-finding, load analysis and cutting pattern generation. These will generally be undertaken numerically using an integrated suite of specialist finite element software.

Detailed reviews of numerical analysis methods for tension structures have been given elsewhere[2,3]. There are two basic approaches to the solution of the overall problem of form-finding and load analysis that have been developed and applied in practice; matrix and vector methods.

The matrix methods are typically an application of more standard non-linear structural analyses such as the Newton-Raphson method [4]. The structure overall tangent stiffness matrix is solved incrementally until convergence is obtained. Special controls limiting the maximum incremental deflections and nodal residual forces may be required. The stress/strain relations for the individual components are coupled with the equilibrium and compatibility requirements for the complete structure.

In vector methods the conditions of equilibrium and compatibility are de-coupled until convergence to an equilibrium solution. The most common of these are Dynamic Relaxation (DR) [2,3] and the Scaled Conjugate Gradient Method [5]. The former has gained the most acceptance for the analysis of tension structures because of its clear physical analogy and ease of implementation of the necessary controls and constraints. Individual element stiffness relations are held separately, which greatly eases the specification of stress controls at form-finding and non-linear, stress dependent, elastic properties under analysis. It is similarly straightforward to introduce a wide range of boundary conditions that can themselves be dependent upon the current deformed state of the structure.

A further method has been applied specifically to the form-finding of tension structures. This is the Force Density method, described originally by Scheck [6]. Although used to date primarily with equivalent cable-net models, recent research in France has extended the concept to triangular surface elements, under the name of the Surface Stress Density Method [7]. The advantage of the method is that it provides a linearised solution to the equilibrium shape finding problem. The controlling element variable is that of force density or tension coefficient, (for example T/l for a cable element of current tension T and length l).

As noted in [7], the main drawback of density methods is that the final distribution of stress is difficult to control. This can be overcome by iterating with updated force densities until the desired smooth stress distribution is achieved, but this would seem to negate the advantage of a linearised solution. Once a form has been found, a vector or matrix method must be used to analyse its response under load.

Inland Revenue Centre Nottingham

At Tensys we have developed and support a Dynamic Relaxation based program suite in house. We continue to find DR well suited to tension structure applications and particularly flexible when being extended to tackle new problems against a time deadline.

What is most important, however, is that the engineer understands clearly the software he is using and the principles underlying its computations. Provided the final solution is both correct and fully understood, then the route taken to achieve that solution is ultimately not important provided it is reasonably efficient. Even the question of solution efficiency becomes ever less critical with the ever increasing computational power currently available. The overall efficiency of the process is still heavily dependent upon the experience of the analyst and the amount of thought before each cycle of the iterative process.

4. Necessary Features of Tension Structures Design Software

When considering the design or purchase of tension structures software there are a number of key features that should be considered. These are an integral part of our DR implementation. In particular the design of a structure should not be constrained by any software limitations.

Understanding of the Method Used

The engineer should have a clear understanding of the software and its limitations. This includes the solution algorithm and how it will respond in particular situations, such as when a local region of the structure is unstable (either due to element collapse or physically inadmissible controls during form-finding, or to excessive membrane wrinkling or beam buckling under load analysis). Understanding and interpretation will be greatly helped if there is a clear physical analogy underlying the analysis method.

It is also important to understand how constraint conditions and applied loading are applied and any inherent approximations.

Tension structures, large or small, are non-linear systems which require careful engineering thought. The use of 'black box' software wherein structures are 'designed' and built without a full understanding of their behaviour should be resisted at all costs.

Control over surfaces stresses during form-finding:

The satisfactory long-term behaviour of a membrane structure requires either a uniform or smoothly varying distribution of stress within the warp and fill directions of the fibres. This will minimise the chances of the development of wrinkles or local stress concentrations under load.

Mercedes Benz A-Klasse :Launch Structure

As the stress distribution is a function of membrane surface relative curvatures, or shape, and vice-versa, the availability of suitable controls during form-finding is essential. Our software determines an equilibrium shape for a specified membrane stress distribution. This distribution may be uniform in both warp and fill directions so as to achieve a minimal surface (eg Inland Revenue and Saga) or constantly varying in all directions to match the designers requirement (eg A Klasse launch structure).

Control over fabric weave orientation during form-finding and analysis:

Ideally the fabric weave directions should coincide with the directions of principal curvature of the surface. For example, the radial patterning of a simple conic tent, or the high point to high point seam trajectory of a parabolic four-point sail. This will optimise the stiffness of a given form, enabling easier initial stressing of the membrane and reducing surface deflections under load.

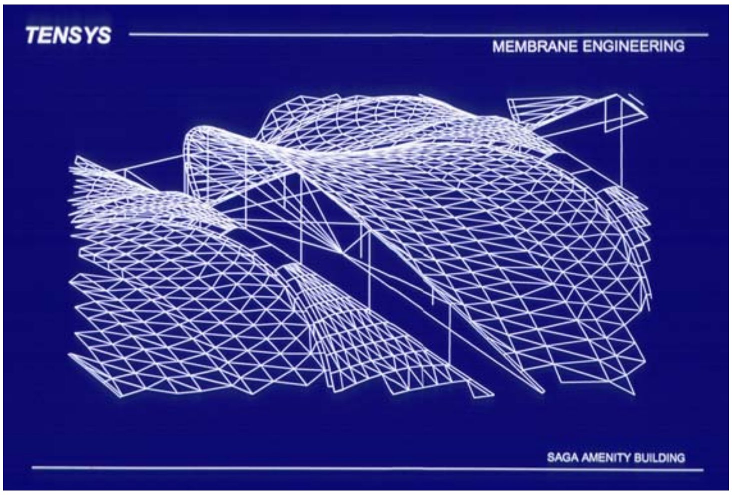
Although it is clearly difficult to optimise the seam trajectories for more complex surface shapes, the analytical procedure should permit the clear specification of material orientation at the form-finding stage and pass this through to the assignment of element elastic properties for subsequent load analysis.

The actual practical choice of whether the material warp or fill direction will follow a particular direction of principal curvature may be will be governed by requirements of strength, installation strategy and fabrication economics.

Availability of a full library of element types:

Membrane should be numerically represented by triangular or quadrilateral finite elements, rather than by an equivalent grid of cable elements. At the form-finding stage, when element size and shape may change significantly during iterations towards equilibrium, smoother stress control is possible by definition of a constant force per unit width.

The alternative equivalent cable-net idealisation is insufficient, making accurate stress control difficult and inaccurate modelling in cases such as the interaction with boundary cables when one weave direction is essentially parallel to the boundary. In this latter case, unless an exceedingly fine cable mesh idealisation is employed, the edge cable will essentially only be loaded by cable elements perpendicular to the boundary.



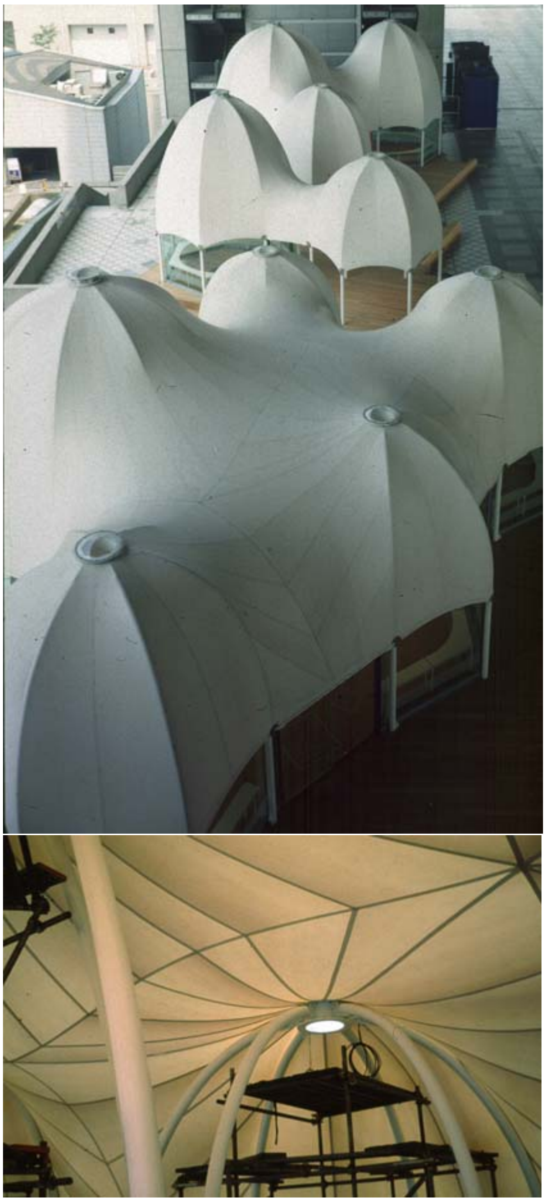
Under load analysis finite elements permit the introduction of cross-stiffness terms representing the ‘crimp interchange’ between the warp and fill fibres and also enable the modelling of the shear stiffness of the coating. They also provide a convenient basis for the computation of updated wind and snow loading according to current deformed geometry.

It should also be possible to model the stiffness of membrane seams. This can have a significant effect when analysing, for example, a conical membrane where many seams come close together at the top pick up ring and effectively provide local reinforcement to the base membrane at this region of maximum stress under snow loading.

A full range of cable, strut and geometrically non-linear beam elements should be available to model the supporting structure [8].

Patterning and Seaming:

The basic orientation of fabric has been discussed above. Individual panels are cut from rolls of material of known width. The cutting patterns themselves are obtained as a two-dimensional approximation to a strip of material taken from the curved three-dimensional structure surface. This may be achieved, for example, by the geometric unfolding of a set of sequential triangular finite elements into a plane.



Edo Tokyo Museum

The use of geodesic seam trajectories helps to optimise the use of material by providing a set of 'balanced' patterns with equal material angles either side of a seam node. This eliminates the generation of 'banana' shaped panels. The shearing together of pairs of adjacent panels enables the better representation of surface curvature in the fill direction. This is particularly relevant when there are relatively large localised transverse curvatures (eg Edo Tokyo Museum).

The generation of geodesic seam trajectories [9], and consequent assignment of principal stress / weave directions, should be fully integrated with the form finding process. Cutting patterns are then generated directly from the form model. This ensures full compatibility between design intent and the realised structure, provided of course that the necessary material compensations have been measured and applied correctly.

Data generated should be both readily interpreted and shared :

Finite element models of major tensile structure projects may well involve tens of thousands of elements and node points. Tools such as graphic visualisation and summary and collation reports are necessary to help the engineer interpret the results of an analysis and convey it to others, such as checking authorities.

Surface form data may be shared with other members of the design and construction team via standard data formats, such as DXF. This also gives access to standard visualisation packages rather than including such sophisticated presentation facilities within the tension structures package itself.

Patterning data must be provided in the form required by the fabricator, both to optimise his efficiency and to minimise errors. This might be a particular graphic format for paper based output, or the direct generation of information in a format suited to a computer aided plotting and cutting system.

5. Project Application : The Chicago Beach Tower Hotel

The building is a 'V' shaped concrete/steel luxury hotel constructed on a small man-made island as a part of the Chicago Beach Resort development in Dubai. It is constructed around a central concrete core at the base of the 'V' with an atrium closure wall of fabric and steel which is 50m wide at its widest and 170m tall.

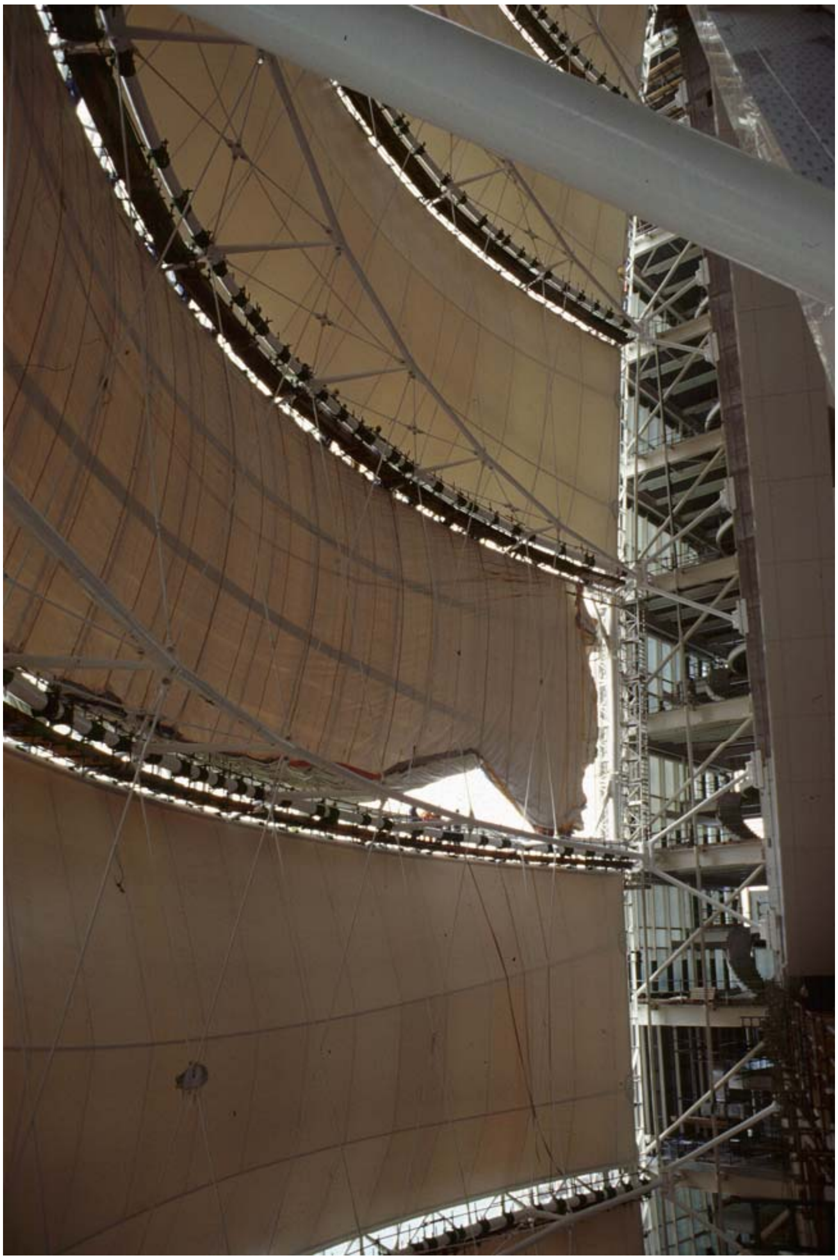
The fabric wall itself consists of 2 layers of membrane separated by a gap of approximately 550mm. The inner membrane will comprises 7400m2 of type II PTFE/glass and the outer 7600m2 of type IV PTFE/glass. The wall is divided into 12 panels of approximately 12.7m in height which are supported off of steel trusses which span horizontally back onto the main walls of the building by means of articulated wishbone connections.

A system of hanger rods provides additional vertical support for the trusses which are formed from thick walled circular hollow sections. Each fabric panel incorporates 2 number lines of slip cables on the membrane surface to assist the fabric in resisting wind suction forces.

Tensys were appointed by WS Atkins, the project engineer and architect, to provide analysis services during the development of the design up until tender. Subsequent to the award of the fabric wall contract to KOCH Hightex GmbH, Tensys were appointed by them to provide full membrane engineering services on what was then a design and build contract based upon the engineers intent.

A model of the complete wall structure was established utilising beam, cable, strut and membrane elements with additional representation of the flexibility of the support systems at the entrance canopy and at levels 18 (intermediate support floor at 135m height) and level 26 (the wall top at 190m). An additional major piece of work related to the determination of the system geometry for all components of the structure. This was undertaken utilising a MathCAD model which eventually expanded to some 100 A4 pages. This was independently verified by the steel subcontractor using his 3 dimensional CAD software.

The design brief outlined a variety of loadcases that had to be evaluated. These included a variety of wind cases (data provided from a comprehensive set of wind tunnel tests), fabric and hanger rod failure cases, thermal movements and, in particular, building creep and settlement. Collated results from these working load cases were factored by appropriate partial safety factors for direct use by the steel subcontractor in his design process.



Of concern was the effect upon the hanger rod forces with the inclusion of building creep/settlement. With a potential movement of 50/60mm over the height of the wall the increase in rod forces was considerable. Site monitoring of building movement allowed for a more precise set of data to be used for erection analyses.

The erection analyses also provided data on anticipated structural movement of the support trusses which could then be used on site to review the erection process. These erection cases were investigated by numerically considering a reversal of the actual installation process. Starting from the final stressed state fabric was progressively removed until only the steel support system remained. The installation of the steel was then studied by progressive removal of hanger rods and trusses.

On site the inner and outer panels of fabric were connected to their upper horizontal steel truss whilst on the ground. After furling and protection the trusses were progressively lifted into position on the tower from the top downwards using each as a lifting frame for the one below. Unfurling and stressing of the membranes could commence once all trusses were installed and the hanger rods pretensioned correctly.

6. References

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