
COMPUTER TECHNIQUES FOR THE DESIGN AND FABRICATION OF MEMBRANE STRUCTURES

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INTRODUCTION

Membrane structure applications have paralleled the rise in both fabric and computer technology. The difference is that whilst demand for suitable fabrics has driven the quest for stronger and longer lasting fabrics it is the computer that has allowed the fabric structure industry to develop to the stage it has reached today. Without the availability of computers and suitable application programs there would be no membrane structure industry.

Prior to computer power there were tents and even the occasional true tensioned membrane structure. These were designed and built by the pioneers of the industry using scale models, crude mathematics and their ingenuity to overcome the problems of invention. What they achieved was remarkable.

An industry could not develop on this basis. Design tools were needed to allow the freedom to design structures that were not simple mathematical derivatives without the need for laborious and costly models. The arrival of the microprocessor in the late 1960's and the ensuing development of suitable software brought these tools.

This paper seeks to examine the use of computers in the development, design and construction of membrane structures from the perspective of a practising fabric structure designer.

THE FINITE ELEMENT MODEL

Membrane structures are an assembly of fabric, cables, beams, struts and anchors arranged in a structurally stable way. Prestress is applied to these components to achieve the form and integrity required. The problem facing the designer is how to represent these components and predict the performance of the assembly in service.

As previously mentioned one route to take is to build a scale model. Another is to try to write a mathematical expression for the entire membrane surface. This is only realistically possible for simple symmetrical shapes such as a hyperbolic paraboloid (hypar). Neither of these methods is really useful for predicting structural performance.

Almost without exception the technique used today is the finite element method. In this method the surface of the membrane is represented by an array of connected segments for which the mathematical representation is relatively simple. For example the smooth continuous surface of the membrane may be represented by a finite number of triangular elements connected at their edges in a way that follows the three dimensional surface closely. Similarly, an arcing catenary cable can be represented by a series of straight elements connected end to end. The data describing the geometry, connectivity ,material properties and load state is called a Finite Element Model (FEM).

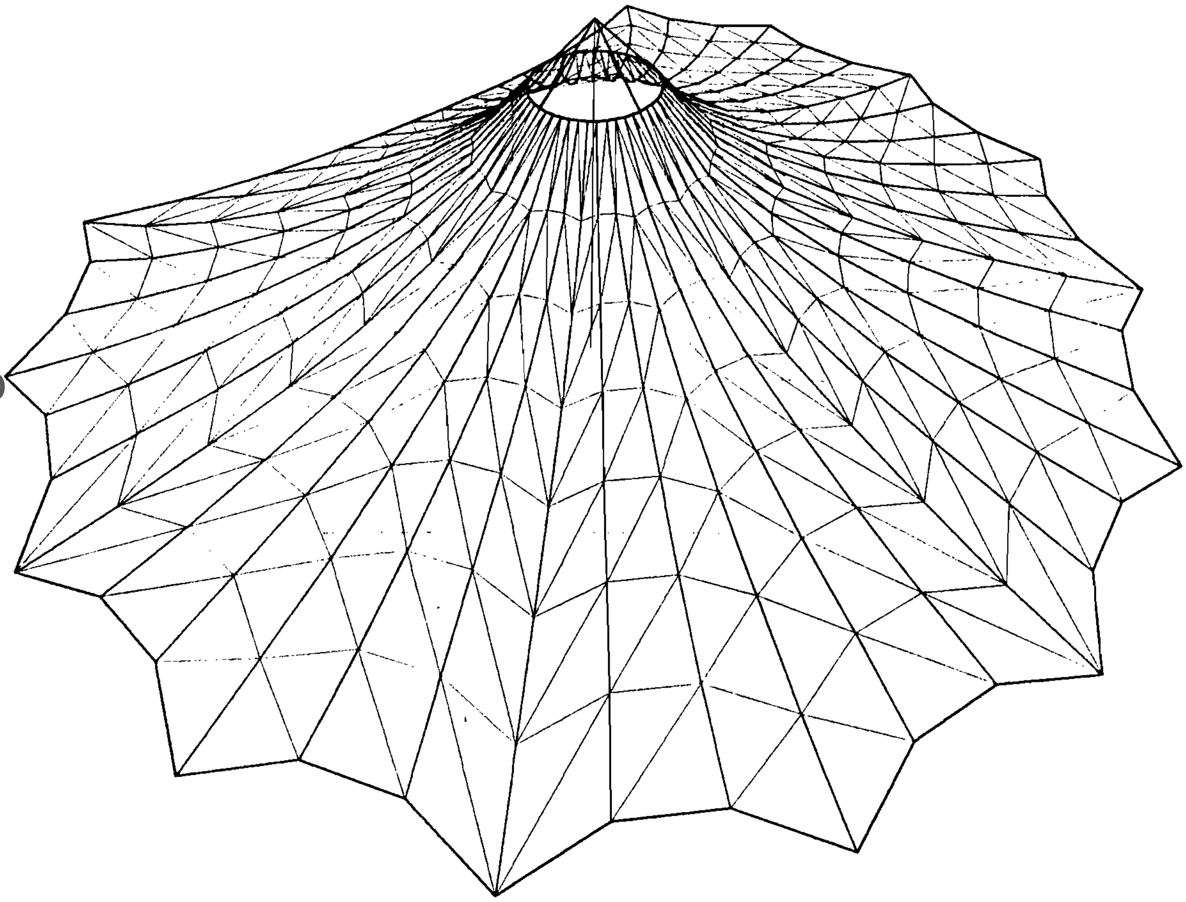

Fig 1. A Finite Element Model

MODEL GENERATION

The first step in generating a finite element model is to sketch the designed structure noting fixed points and edges, cables, struts and beams. As with all structural design, an initial estimate of the constituents of the structure is required. An experienced designer will be able to make a good judgement of the required prestress in the membrane and cables, and of the grade and size of all components.

With all basic geometric and material data at hand assembly of a finite element model can begin. Finite element method computer programs usually come in two parts. The main component is that part which analyses the structure for applied internal and external forces to produce a result. The other component, known as a pre-processor, is used to generate and edit a finite element model. In terms of design office efficiency the pre-processor is the most important.

The perfect preprocessor would allow the designer the ability to alter basic geometry, mesh density and material properties with as much ease as pushing and pulling on a lycra model. Such a pre-processor is not far off. Today, graphical interfaces and journal files recording impact sessions allow anything from massaging to major surgery with relative ease.

SHAPE FINDING

After a finite element model has been generated it is necessary to alter the geometry (other than fixed points) to achieve a form which is in equilibrium. Generally it is desirable to have the fabric uniformly stressed and cables to be evenly tensioned throughout their length. For some shapes it is not possible to achieve these aims and so a whole repertoire of "tricks" can be used to force a desirable solution.

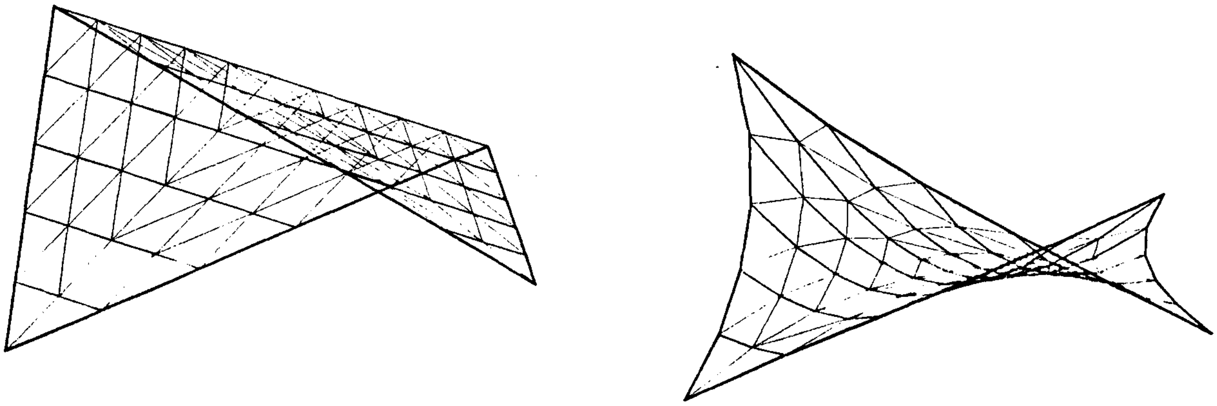

Fig 2. Initial Shape Equilibrium Shape

Other desirables include the ability to vary warp and weft stresses, to fix a particular cables length and to include gravity loads particularly for large span flat structures.

It is the ability to arrive at a mathematically stable shape which gives confidence to the designer that the structure can be successfully built.

ANALYSIS

To fully engineer a membrane structure it is necessary to predict its performance. In service deflections, stresses and reactions must all be calculated and catered for, as they are in conventional building design. The fundamental difference between a membrane structure and a conventional structure from the analysis perspective is the magnitude of the deflections resulting from loads.

In essence a membrane structure derives a large component of its stiffness from its shape. As its shape changes under load so does its stiffness. A flat tensioned sheet, whilst stable in equilibrium, must deflect to generate resistance to a disturbing wind pressure. It has zero stiffness in its flat equilibrium state and generates increasing stiffness as it deflects under load. This is the problem of geometric non linearity that the FE analysis must cope with.

There are two principal mathematical techniques used in commercially available software to solve the structural analysis. These are (1) Conventional matrix techniques with iterative methods such as gaussian reduction or (2) Nodal force balancing with techniques such as dynamic relaxation to speed solution. The details of these methods are well beyond the scope of this paper and are best left to experts in the field.

Both these methods have advantages and disadvantages. The chief advantage of matrix techniques is the relative speed of solution, especially for larger structures. For force balancing methods it is not necessary to write and reduce large matrices and hence demands on computer hardware is less.

A further source of structural non-linearity is the non linear stress - strain response of fabrics under load. In practice however this makes very little difference. For typical fabrics over the working range of stresses in fairly standard type of structure (up to 10 kN/m) the stress-strain relationship is very nearly linear. What difference any material non-linearity does make is swamped by geometric non-linearity.

Because membrane structures deflect so much under load, applied loads may alter as the surface changes shape. It is necessary to re-write the applied loads to "follow" the deflected shape as the analysis converges to solution. This is particularly so for pressures which act normal to the membrane surface. It is even possible in extreme cases that the total magnitude of the load increases as the membrane stretches and increases its surface area.

Usually loads are applied incrementally, increasing in steps towards the maximum. This allows convergence at each increment of load which enhances the overall ability to find a solution to the non-linear problems as well as ensuring the loading at the last increment is representative of the final displaced shape.

USE OF ANALYSIS RESULTS

A computer can generate a large amount of data. With FE programs this is taken to extremes. Printed output for a single load case on a small structure can amount to dozens of pages. For a large project with multiple load cases the sheer volume of paper can make the subsequent design process extremely laborious.

Result summaries giving maximum membrane stresses, deflections and cable loads are of limited value as these figures may not be representative of the whole structure.

Graphical presentation of results is of far more value. The extent of maximum stresses or of slack areas can be readily seen as can deflections (either total or the x, y & z components) by use of a variety of colours. Cable forces can be quickly viewed and an appreciation gained as to how the structure is working and what steps will enhance its performance. This is of immense benefit to the designer trying to optimise the use of materials within the structure.

Other information such as contouring of the surface can help with checking for adequate drainage of the surface.

Automation of cable sizing has allowed very quick checks of preliminary design assumptions. Conversion of beam and strut result data into a format suitable for the LIMSTEEL design program to AS 4100 (or other suitable program) enables speedy design of these components. Alternatively, reaction reports allow communication of results to other engineers to aid with the design of supporting structures.

Conversion of the three dimensional computer model into an Autocad drawing via a DXF interface is an invaluable feature. Design drawings can proceed using these as a base or details for particular components can be overlaid and visualised. More usually this feature is used to generate high quality three dimensional views and presentation graphics to aid with the visualisation of a concept.

PATTERNING

The single most important use of a FE model after ensuring structural stability is its use in generating patterns. Prior to the advent of specialist software, patterns for tents were a matter of the tent makers art. Early tensioned membranes were patterned from scale models in stretch fabric using various means of measuring to accurately find x, y and z co-ordinates from which to generate patterns.

These are two methods for the generation of patterns using FE models.

1. Representing the surface with triangular elements and folding these out consecutively along the common sides onto a plane.

2. By taking an area of the FE Model and using FE techniques to squash it onto a plane.

Both methods require that the edges of the patterns be along suitable lines such that unnecessary wastage of fabric be avoided. These lines are the shortest line within the surface between the endpoints of the desired seams and are known as geodesic lines.

In the first method the original triangular finite elements can be folded out if the end points of the patterns are at a suitable position to maximise fabric usage and the intermediate modes lie along a geodesic. Alternatively geodesics can be calculated over the FE model between defined end points and intermediate points on each geodesic can then be used as the vertices of a new triangulation.

The second of the above methods has the advantage of reporting the stresses which result from forcing the flat fabric into a three dimensional curved surface. This can be used as a guide as to the likelihood of the pattern developing wrinkles in service in cases of extreme curvature or where extra wide patterns are used.

Of course both methods must account for the elastic stretch in the fabric whilst being tensioned as well as any construction stretch or bedding in that may occur. This is done by scaling down the flattened patterns by an appropriate factor in both the warp and weft directions.

Cutting patterns must further be processed to smooth to a curve the series of straight lines representing the edges of the triangular elements . Piecewise cubic splines have been found to result in a good curve. Alternatively plotted points can be smoothed on the shop floor using a flexible rule. Marking radii for cable edges or curved fixed edges is another problem that must be tackled in a similar way.

Patterns can be presented as a scale drawing with co-ordinate information attached or if the fabricator is equipped with a plotter they can be presented digitally for direct conversion to the fabric.

In the latter case a lot more information can be supplied. Fabric pocket allowances for cable sleeves can be directly plotted with match lines for welding. Membrane plates can be premarked on the pattern for rapid and accurate fixing at a later time. In short nearly all fabric details can be included on the patterns leading to faster assembly of the structure. Another benefit of rapid electronic plotting of patterns is the reduced reliance on structure symmetry to achieve economies. Savings can be made when hand plotting by only marking one pattern and then multiple layer cutting to make the number of similar patterns required.

The most important gain of direct fabric plotting is the increase in quality resulting from the accuracy of the conversion. Consistent accuracy of plots of +/- 1 mm are achievable. With manual plotting there is always a risk that one or more points will be misplotted with inevitable consequences to the finished structure. Experience has shown that no flaws or wrinkles in a finished structure could be blamed on patterning or conversion where a plotter has been used.

CONCLUSIONS

The successful use of membranes in architectural and structural applications is now dependant on computer technology. The finite element method is the core of the process of design. Programs to generate, solve and use finite element models of structures are essential to the effective operation of a membrane structure design office.

As computers continue to develop so will the expectations of their applications. This will apply to tensile structures as larger span and more irregular structures are built. Pressures for greater economy in construction can only be met by the smart use of these technologies as they become available.

Despite all great advances in computer technology nothing can replace the imagination of the architect who conceives a form, the judgement of the engineer who designs the structure or the experience of the fabricator who assembles and erects it.

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15.500	-1.348
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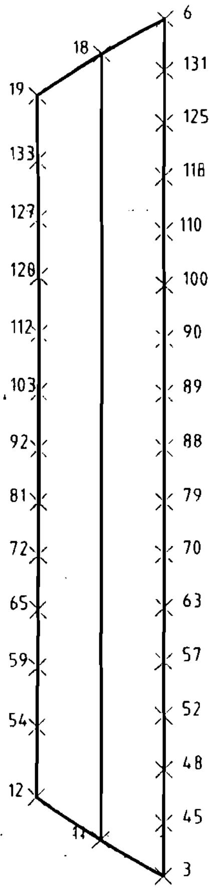

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3.500	1.328
3.000	1.328
2.500	1.329
2.000	1.330
1.500	1.332
1.000	1.333
0.500	1.334

Compensation:- WARP 0.0033
:- WEFT 0.0333
SCALE 1: 100 UNITS METRES
11:23:28 03-23-1993

Job Name: SUNSHINE PLANTATION
Job No.: 9208/903 Pattern No.: spsdp3

Typical Fabric Pattern

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SCAB - 1.11               CABLE SIZING SUMMARY               04-19-1993
JOB: HIGHWAY NISSAN - EQUILIBRIUM                           Page: 1 of 3

DATA FILES: HIGHWAY NISSAN - EQUILIBRIUM
            HIGHWAY NISSAN - WIND UP
            HIGHWAY NISSAN - WIND DN
DESIGN LOAD FACTORS - EQUILIBRIUM:  3    APPLIED LOADS:  2

GROUP  1
CABLES: 1 2 3 4 5 6 7 8
APPROX LENGTH:  15.2     MAXIMUM FORCE:   55.0 kN
LOAD CASE: HIGHWAY NISSAN - EQUILIBRIUM
CABLE              SIZE      MAKE    STRENGTH  CABLE    CAPACITY FACTORS
TYPE               (mm)       UP      GRADE   CAPACITY  APPLIED  EQUIL
NORSELAY           16.0      7x7       2070   176.6                3.21
STAINLESS                 no size available
STAINLESS          16.0      7x7       GR 3   165.8                3.01
STAINLESS                 no size available
GAL STRAND         14.0      1x19      1570   173.0                3.14
GAL ROPE           18.0      7x7       1570   183.0                3.33
GAL ROPE           18.0      6x19      1570   169.0                3.07
GROUP  2
CABLES: 9
APPROX LENGTH:   0.8     MAXIMUM FORCE:   12.3 kN
LOAD CASE: HIGHWAY NISSAN - EQUILIBRIUM
CABLE              SIZE      MAKE    STRENGTH  CABLE    CAPACITY FACTORS
TYPE               (mm)       UP      GRADE   CAPACITY  APPLIED  EQUIL
NORSELAY            8.0      7x7       2070    46.6                3.79
STAINLESS           7.2      1x19      GR 3    44.3                3.60
STAINLESS           8.0      7x7       GR 3    44.1                3.58
STAINLESS           8.0      7x19      GR 3    41.6                3.38
GAL STRAND          8.3      7/2.75    1320    51.8                4.21
GAL ROPE            9.0      7x7       1570    45.7                3.71
GAL ROPE            9.0      6x19      1570    42.2                3.43
GROUP  3
CABLES: 10
APPROX LENGTH:   0.8     MAXIMUM FORCE:   12.3 kN
LOAD CASE: HIGHWAY NISSAN - EQUILIBRIUM
CABLE              SIZE      MAKE    STRENGTH  CABLE    CAPACITY FACTORS
TYPE               (mm)       UP      GRADE   CAPACITY  APPLIED  EQUIL
NORSELAY            8.0      7x7       2070    46.6                3.79
STAINLESS           7.2      1x19      GR 3    44.3                3.60
STAINLESS           8.0      7x7       GR 3    44.1                3.59
STAINLESS           8.0      7x19      GR 3    41.6                3.38
GAL STRAND          8.3      7/2.75    1320    51.8                4.21
GAL ROPE            9.0      7x7       1570    45.7                3.72
GAL ROPE            9.0      6x19      1570    42.2                3.43
GROUP  4
CABLES: 11 12 13 14 15 16 17 18
APPROX LENGTH:  15.2     MAXIMUM FORCE:   55.8 kN
LOAD CASE: HIGHWAY NISSAN - EQUILIBRIUM
CABLE              SIZE      MAKE    STRENGTH  CABLE    CAPACITY FACTORS
TYPE               (mm)       UP      GRADE   CAPACITY  APPLIED  EQUIL
NORSELAY           16.0      7x7       2070   176.6                3.16
STAINLESS                 no size available
STAINLESS                 no size available
STAINLESS                 no size available
GAL STRAND         14.0      1x19      1570   173.0                3.10
GAL ROPE           18.0      7x7       1570   183.0                3.28
GAL ROPE           18.0      6x19      1570   169.0                3.03
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Sample Cable Sizing Results