MacroSpan
– *A New Generation of Lightweight/Longspan Structures*.

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Considerable progress has been made in recent decades in the design and construction of structures to cover very large spaces without internal support. Increasingly, their construction can be justified commercially because of the reduction in costs arising from technical gains and the wide range of uses the buildings they cover can be put to. This paper describes in some detail a concept which adds to the inventory of structures now available to perform this function. The background to its development, its form and construction details are discussed. An explanation of its structural behaviour and the results of numerical studies follow and., from these, material usage and costs. The method of erection and cladding techniques are then explained and the paper concludes with a range of applications for the system.

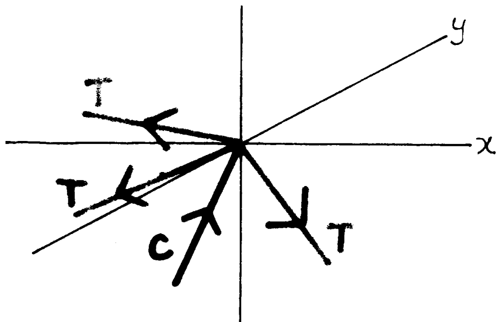
1. INTRODUCTION

Space structures are categorised in accordance with their predominant mode of structural behaviour and this can be described in terms of their mode of resolution of force vectors. There are several different modes of vector resolution and these all obey a simple set of rules. These are that for the force equilibrium of any part of a structure, be it a single node or a segment or the whole of the structure, there must be:

- at least four vectors acting upon it
- these four vectors must be capable of forming a closed circuit in three dimensional space
- the vectors must pass through a common point

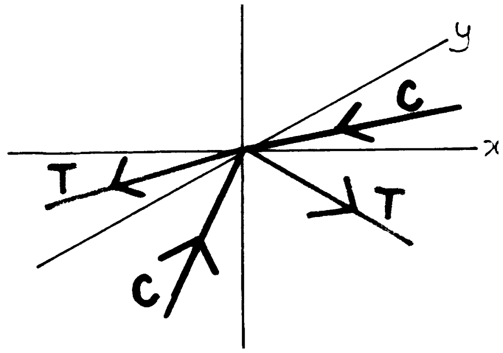
One mode of vector resolution is shown in Figure 1(a) and the rules governing this mode are given. This mode governs the behaviour of Tensegrity structures developed by Buckminster Fuller. The essential feature of these structures is that the ends of the struts do not meet. Many beautiful Tensegrity models and small scale prototype structures have been built but no true large scale Tensegrities have been built for practical use. They appear to have a limitation of scale in that they rapidly become too flexible as the size of the structure is increased.

This limitation is partially overcome by joining the ends of the struts together in pairs. This is shown in Figure 1(b) which represents another mode of vector resolution and the rules for this are also given.



Vector Resolution Type 1
The sum of the angles subtended between the tension vectors must be less than 360 degrees and the compression vector must lie inside the planes formed by the pairs of tension vectors

(a)



Vector Resolution Type 2
The sum of the angles subtended between the vectors must be less than 360 degrees and the vectors must alternate in sign.

(b)

Figure 1 Vector Resolutions

Further studies of this mode led to the development of the generalised structural form shown in Figure 2 which consists simply of a two way network of ties on the outside with an inner network of interlacing struts. Note that the struts only meet in pairs. There are two more ties than are strictly required at each node but this is a consequence of the form.

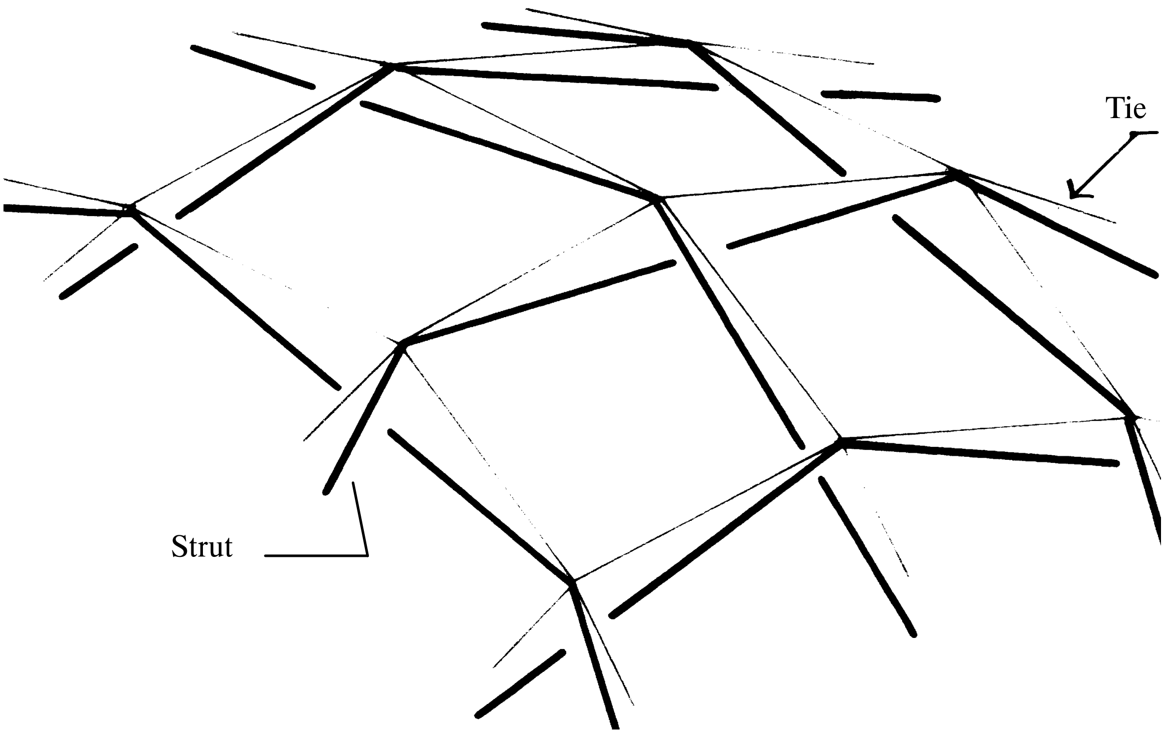


Figure 2

Numerical studies have indicated that, whilst this form significantly increases the stiffness above that of a pure Tensegrity, the resulting structures must be very strongly curved to provide satisfactory structural behaviour for spans greater than approximately 50 metres. This leads to structures which are impractically high for medium to long spans.

These same studies did indicate, however, that these structures are structurally very efficient and they have other characteristics which are also of considerable advantage. The central topic of this paper is a description of the form which evolved from the next modification to these structures. This retains the basic advantages of the form that has been described but also overcomes the problems with stiffness.

2. MACROSPAN

The modification can be quickly seen by comparing Figures 2 and 3. Where a strut is one direction passes under the intersection of the struts in the other direction, a hinge is introduced in it and a tie connected from the intersection of the outer struts to the hinge. This change considerably increases the stiffness of the structure. The reasons for this are twofold: Firstly, the struts are at a much steeper angle to the surface of the structure and, secondly, the forces are more rapidly distributed through the more immediate interaction between the two arrays of struts and ties.

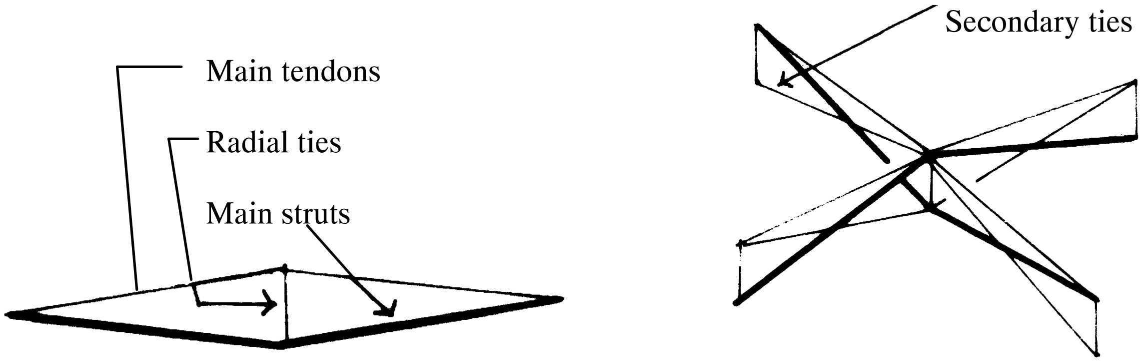


Figure 3 Two Dimensional Element and Three Dimensional Module

Referring again to Figure 3 it will be seen that another array of light restraining ties has been introduced to laterally restrain the inner nodes of the structure.

This is the basic module of MacroSpan.

Figure 4 shows a full assemblage. The structure must be curved in at least one direction and it is also readily curved in two directions. A large variety of shapes can be accommodated within these constraints though regular surfaces, such as circles and spheres, are often preferable because of the repetition in member length and the consequent economies. Shapes are discussed in more detail in a later section.

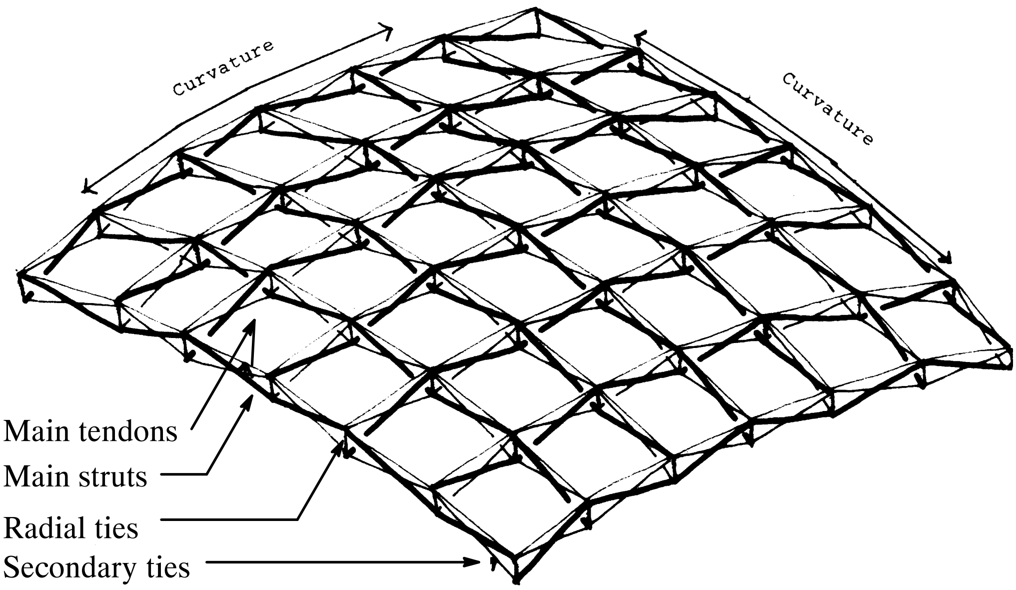


Figure 4 Typical Assemblage

There are four components in MacroSpan, each performing a particular function:

- the main struts which comprise approximately 90% of the weight of the structure and are, therefore, the major cost component.
- the main ties or tendons which lie on the outer surface of the structure and comprise most of the remaining weight of the structure.
- the radial ties which link the inner and outer nodes.
- the secondary ties which laterally brace the inner nodes of the structure.

The two major components, the main struts and the main tendons, are shown in Figure 5 which shows alternative forms which can be used. Note that for the radial ties either strand or tubular sections can be used and the second alternative is discussed in more detail later. The restraining ties are light wire strand.

TENDONS: Stress relieved high strength strand arranged –

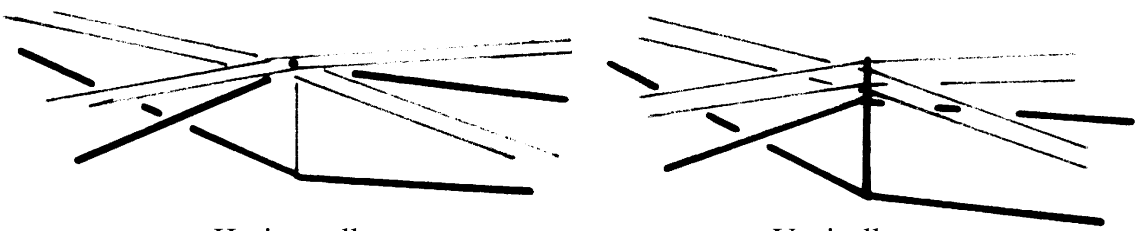
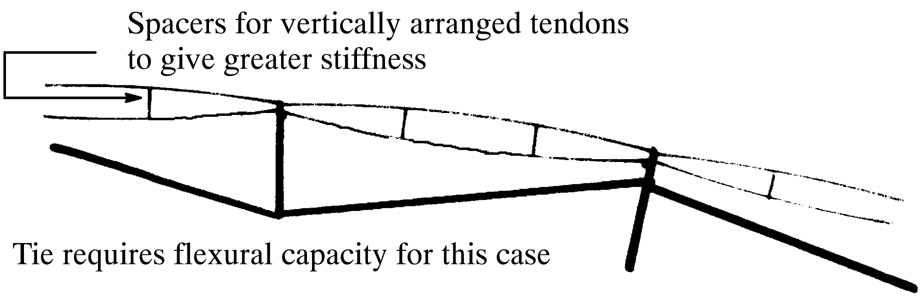
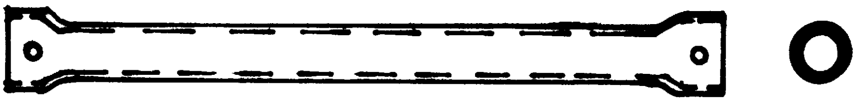


Figure 5 Components



STRUTS:



Single tubes with swaged ends

Composite tubular struts

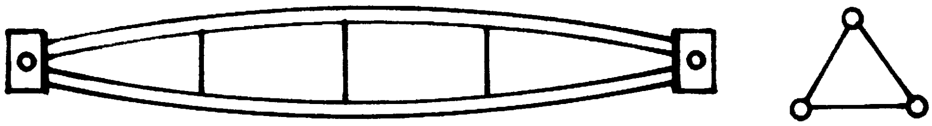


Figure 5 (Cont.) Components

In most cases the weights of the struts can be kept to a minimum by using high strength (grade 350) steel and minimising the effect of slenderness ie. the steel in the struts is stressed to its maximum permissible value. In reality, there is a balance between the material and fabrication costs and the length of the struts. This means that for struts of length in the range up to approximately 9 metres single tubular struts are most economical, even though they will not usually be stressed to their maximum permissible value because of slenderness effects. Above this length, fabricated composite struts are more advantageous since the savings in material cost made by stressing to the maximum permissible value will exceed the additional costs of fabrication.

Figures 6 shows typical connection details for the structure utilising, in this case, tubular radial ties and the main tendons are arranged vertically in relation to each other. The points to note about the details are:

- the tendons run continuously through the extension of the radial tie and are fastened to it by clamping each side. No cutting of the tendons between the node points is required which leads to simplicity of assembly and economy.
- the pin connections for the main struts to the radial ties allow large rotation of the struts in a vertical plane as the structure is erected. The connections are not snug tight but rather allow a little movement which provides for the very small horizontal rotations which occur during erection.
- the ends of the main struts are simply cut and slightly swaged thus minimising fabrication costs. The ends of the radial tie tubes are cut and left open.

These connection details are an essential ingredient in the method of erection which is discussed later.

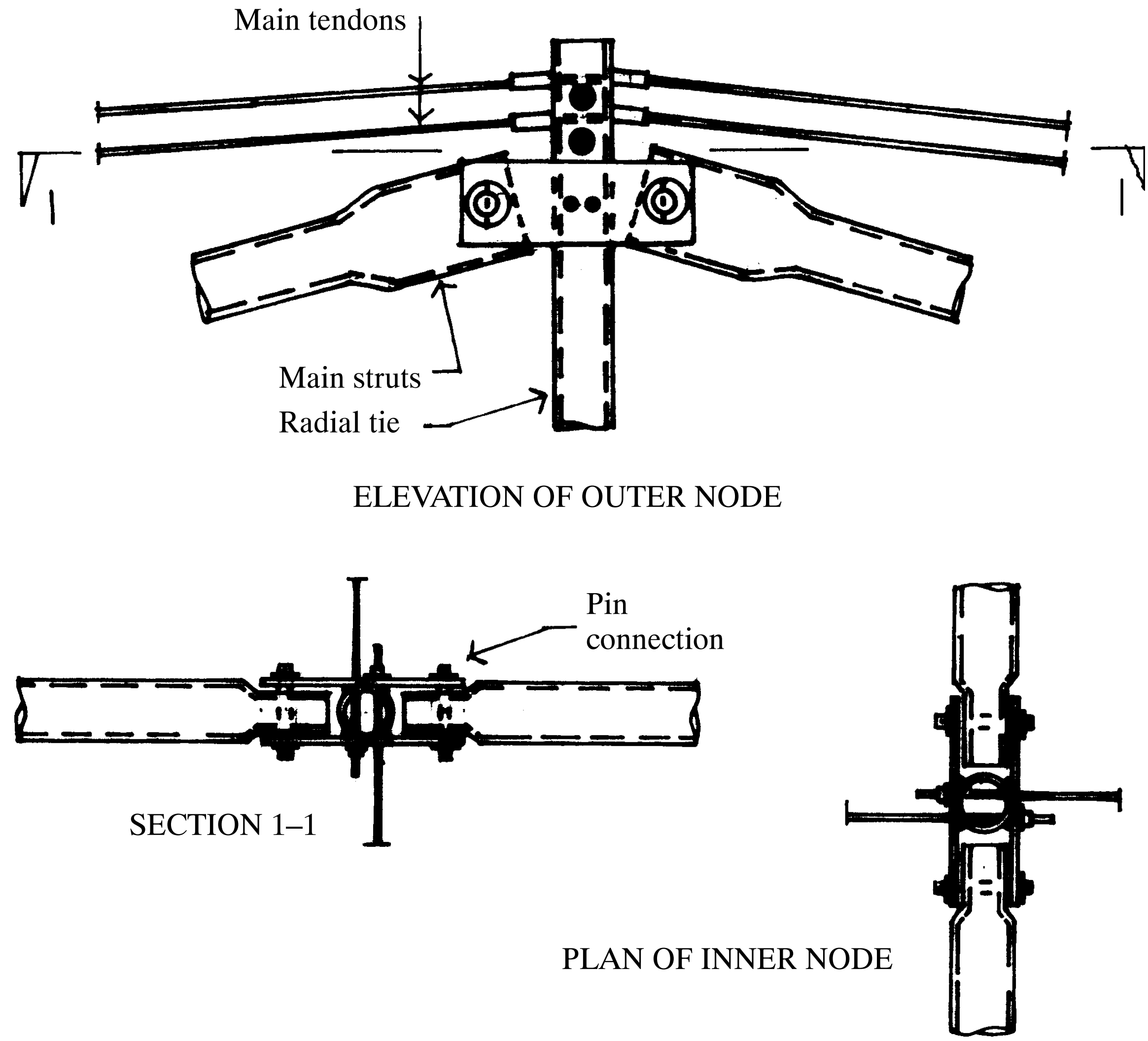


Figure 6 Typical Connection Details

3. STRUCTURAL BEHAVIOUR

Figure 7 shows the basic method of external load resistance of an element of MacroSpan under both inward and outward loads. This demonstrates the inherent advantage of the structure in that the main tendons only act in tension for any load combination. Avoiding the need to design for load reversal in these members provides inherent economies.

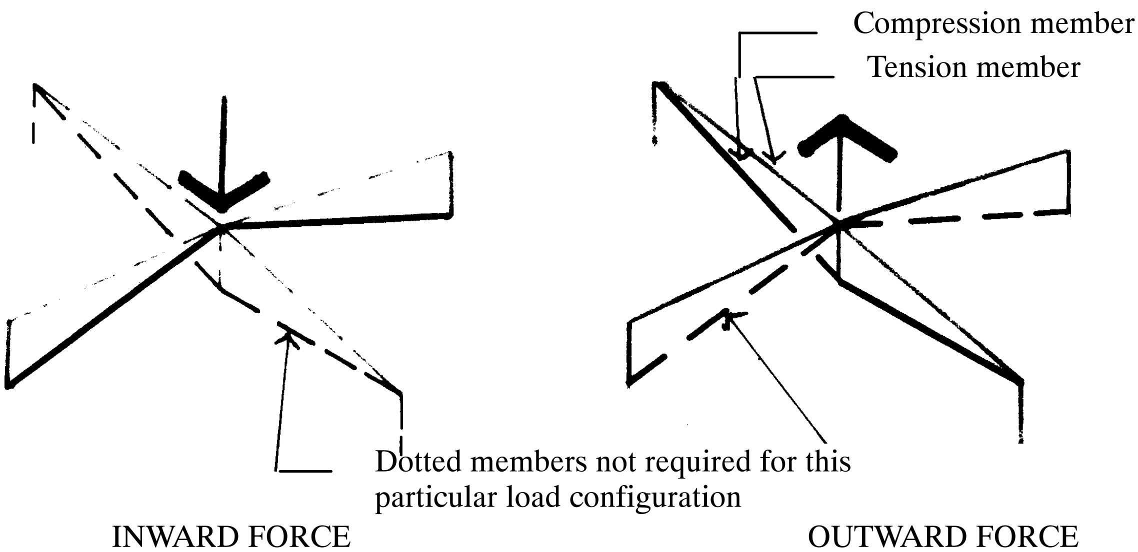


Figure 7 Structural Function of Primary Members (secondary ties not shown)

The main struts have the primary function of resisting compression forces, which is the condition which determines their size. They can also resist tension forces with no penalty in their size.

The radial ties also need only be designed to resist tension forces however, the provision to resist compression forces has advantages, particularly in the erection process, and the cost penalty for this relatively short member is small.

A full assemblage is again shown in Figure 8 indicating, in this case, the primary function of the members; light being tension and heavy compression.

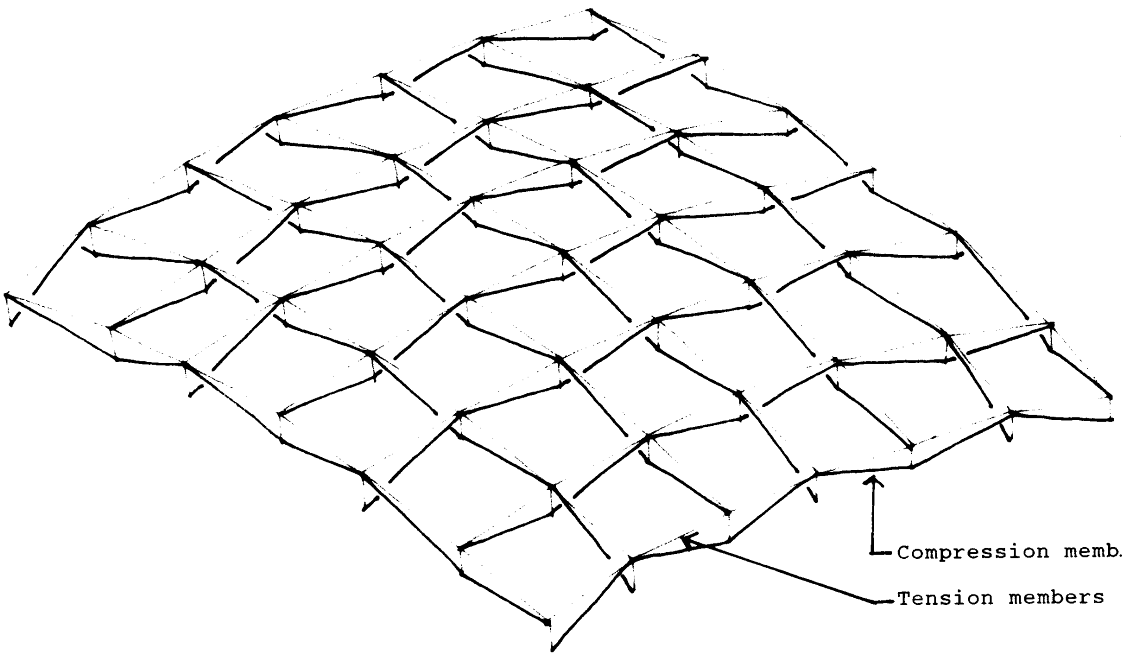


Figure 8 Structural Function of Primary Members (secondary ties not shown)

Figures 9 and 10 demonstrate in principle how inward and outward forces are distributed out in the assemblage. The members represented as broken lines do not perform a primary structural function for the particular load case shown but may be required to provide a lateral restraining force to a node.

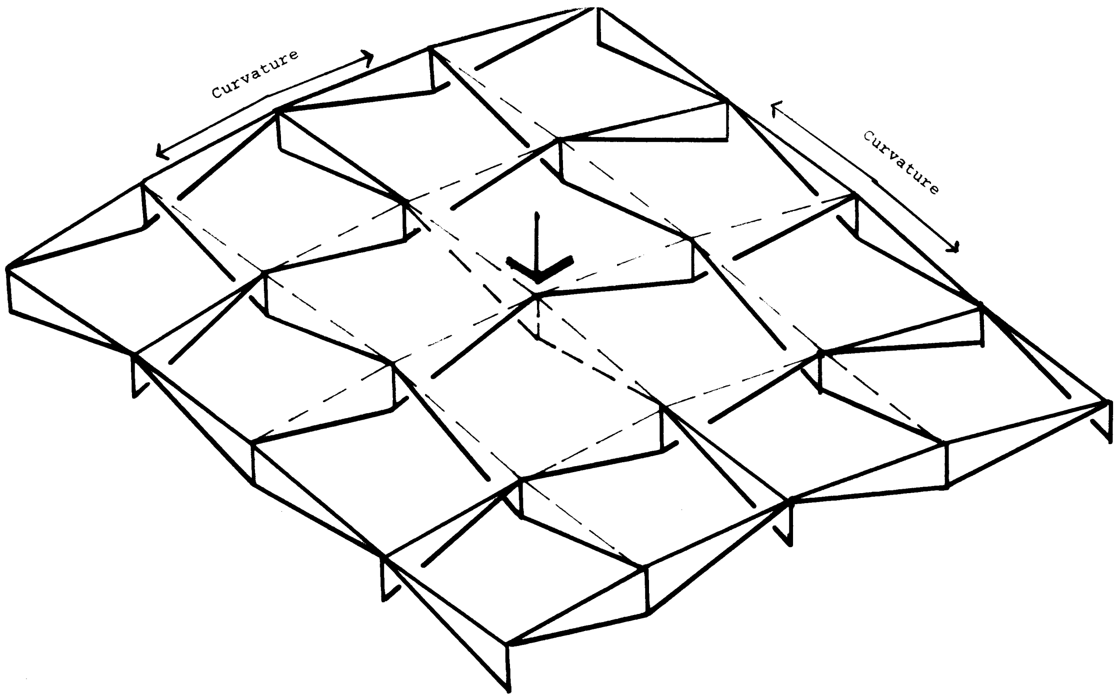


Figure 9 Dispersal of Inward Force

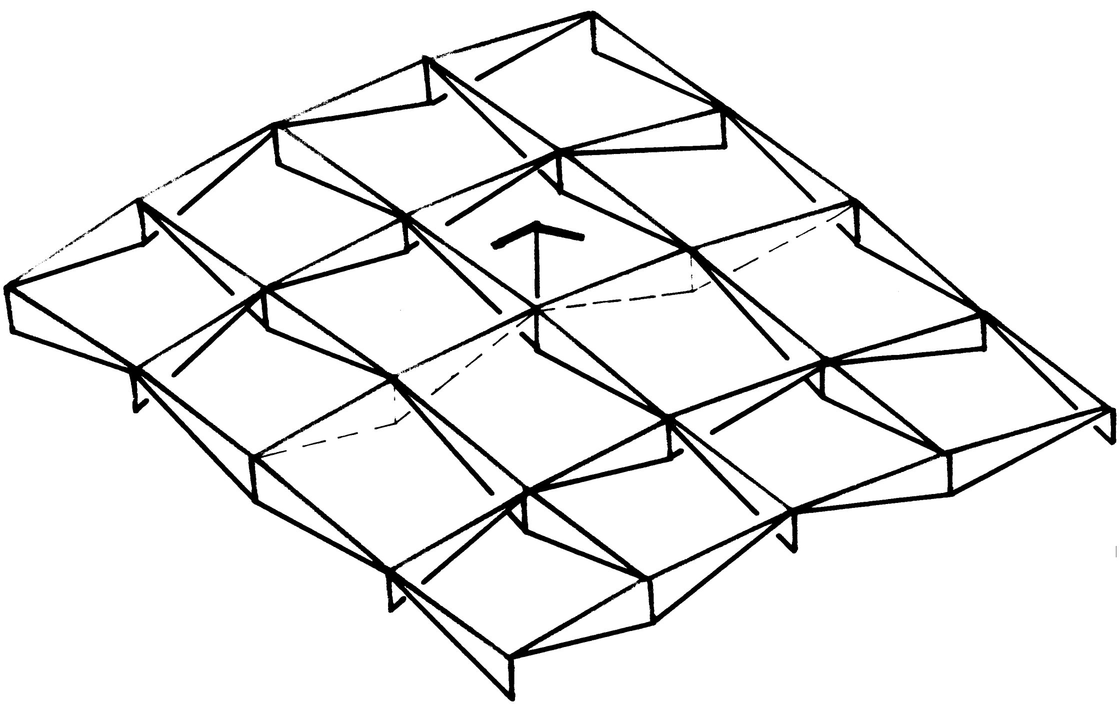


Figure 10 Dispersal of Outward Force

Qualitatively, the behaviour of MacroSpan may be pictured as being that of an articulated arch or shell (the struts) which is constrained to keep its shape by a tensile skin (the tendons); behaviour which is akin to that of a balloon. As for the balloon, the tensile loop must be completed to close the structural system.

An important feature of MacroSpan contributing to its structural efficiency is that it can be prestressed. The pretensioning of the tendons not only induces tension forces into the tendons themselves but also compression forces into the main struts. This is an important advantage, particularly for very long spans, because prestressing greatly assists in reducing deflections under both static and dynamic loading conditions. In addition, it means that high strength materials can be used which is conducive to economy. Prestress can be introduced in two ways: either by direct jacking of the main tendons at their ends or through the erection process. Generally, it will be a combination of the two.

4. SHAPES

The principles of MacroSpan are very simple and it can be used in a wide variety of ways. Structures of regular shape will generally be preferred because of the repetition in the member lengths and the consequent economies. Nevertheless, non–regular shapes can be used so long as the basic rule of curvature in at least one direction is adhered to.

Figure 11 shows the first shape for which the system was conceived. It is based upon a singly curved barrel vault in which the ends are also curved. Typically, the section is a segment of a circle, which results in repetition in member length, but it can also be derived from other geometries such as an ellipse. The barrel vault is the simplest geometrical form for a complete structure because the grid is basically an array of squares which have been wrapped around a cylinder.

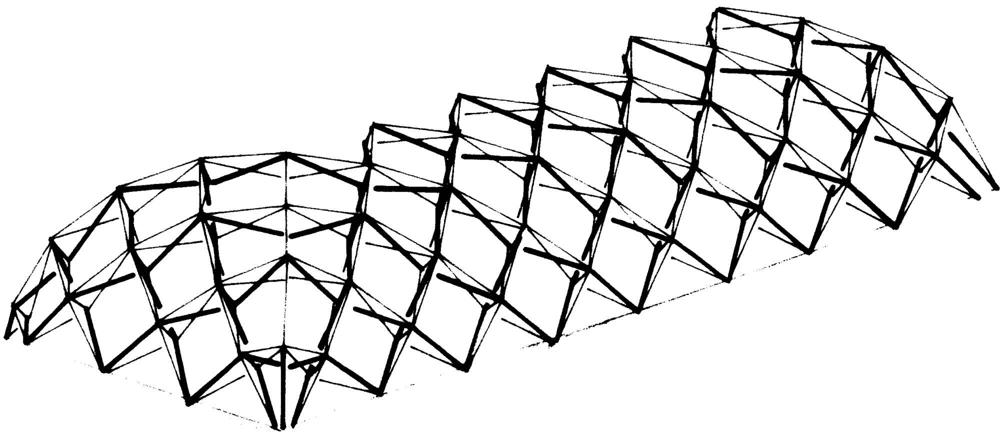


Figure 11 Barrel Vault with Rounded Ends

Figure 12 shows a variation on this in which the ends are vertical. This shape introduces the two dimensional equivalent of the module described before: At each end of this vault there is a form of truss for which the principles are as for the three dimensional arrangement ie. the main tendons and the struts are retained except that the struts now cross each other in the same plane. The crossing of the struts can be readily achieved by using two members to form one strut and one to form the other.

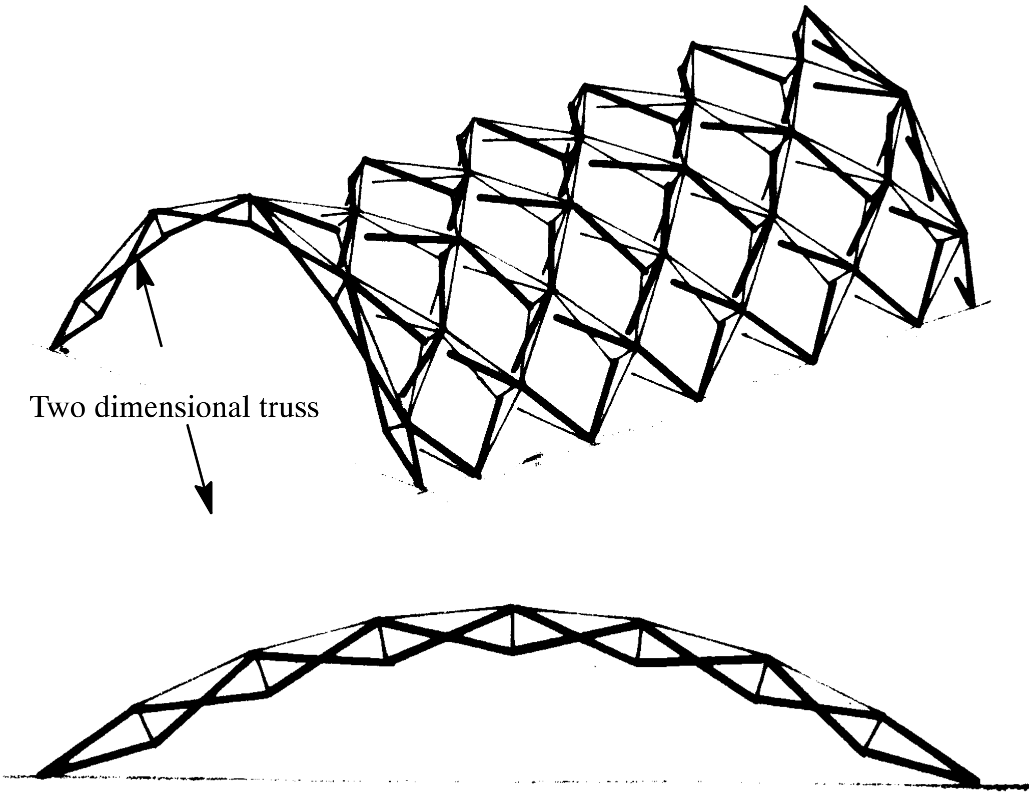


**Figure 12 Barrel Vault with Vertical Ends
and a Two Dimensional Truss**

The truss can, of course, be used on its own for two dimensional applications.

Figure 13 shows a doubly curved shape which is a sphere and in this example the grid is again based upon an array of squares superimposed on the surface. This again has the advantage of repetition in member length but the squares take on a rhomboid shape.

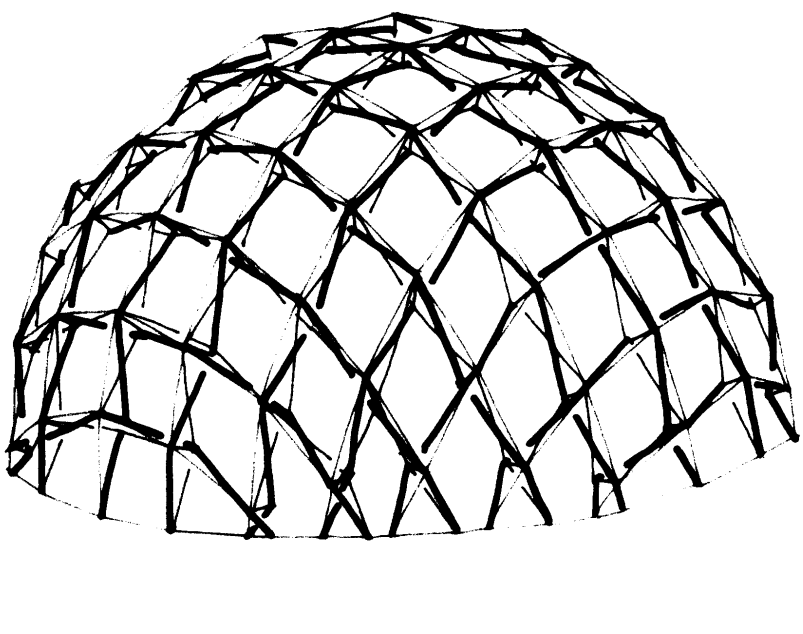


Figure 13 Sphere

The skewing of the squares is quite significant for a full hemisphere but in most cases actual structures would be flatter segments of a hemisphere and the skewing would not be as great. The skewing is of significance for the cladding since it leads to a number of different support conditions for it. Also, the method of erection is affected by the skewing as will be explained in more detail later.

Figure 14 shows a variation on the barrel vault in which a vertical wall is created around the perimeter. In this case the vertical columns would be conventionally framed and interact with MacroSpan to resist lateral forces much as a conventional portal frame does.

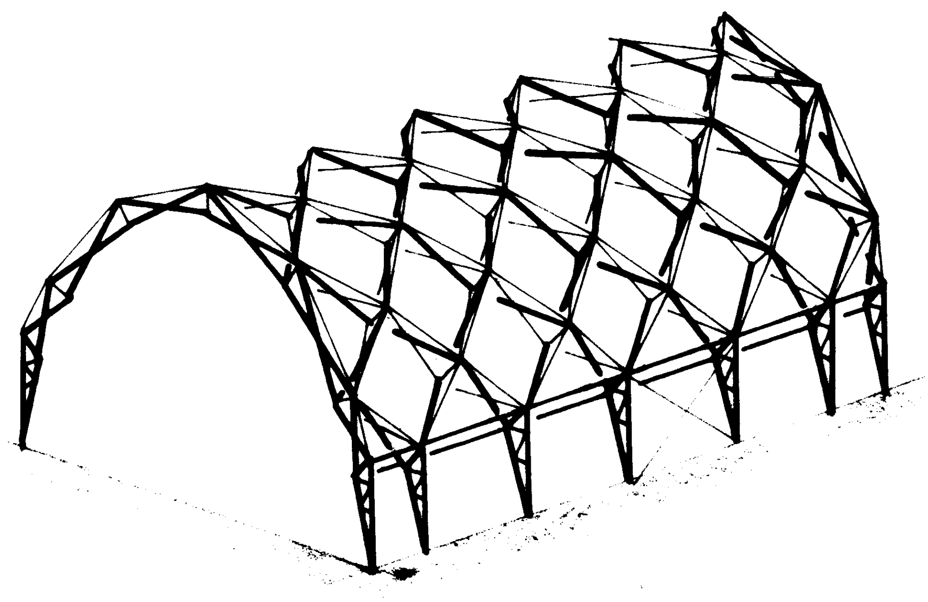


Figure 14 Barrel Vault with Vertical Walls

5. STRUCTURAL ANALYSIS

Most of the analytical work on MacroSpan has centered on the study of the structural behaviour of a barrel vault of the type in Figure 11 with a span of 70 metres.

Initially, the module used was that shown in Figure 2 but, as previously mentioned, the behaviour was not satisfactory. It was found that, for normal parameters of height and level of prestress, deflections were too high. This significantly reduces the curvature of the structure and hence its load carrying capacity. This study established that this module was suitable for only smaller structures with relatively large curvature.

The modification of the module to that shown in Figures 3 and 11 had a quite dramatic effect on the behaviour of the structure, reducing the deflections by approximately five times and forces by one half. For a given level of performance, the forces in the members were also greatly reduced.

The parameters adopted for the analysis of this structure are shown in Figure 15. The governing loading condition was 100% live load on one half of the structure, an onerous loading for a structure of this type and size and one which would probably be reduced in practice to 100% on one side and 50% on the other.

The results of the analysis are also shown and these are well within acceptable limits for a structure of this size. No dynamic analysis of the structure has been undertaken yet but the stiffness and resonant response of the structure is readily adjusted by changing the depth of the structure, the prestress or, if necessary, the size of the members.

Analysis of 70 metre Barrel Vault

Loading parameters (working loads):
- Self weight 0.15 kPa
- Superimposed dead load 0.123 kPa (purlins, sheeting & sarking)
- Live load 0.25 kPa over one half of roof
- Wind load (all uplift)
  - windward quarter 0.02 kPa
  - middle half 0.79 kPa
  - leeward quarter 0.53 kPa

Deflections
Self wt+super dead load=138mm (span/500)
Uniform live load = 126mm (span/550)
Live load over half roof =
Wind load = 176 mm (span/400)

Members
Main struts 324mm dia x 6.4 CHS
Main tendons 4–15 dia high strength strand
Radial ties 101mm x 4.9 CHS
Secondary ties 1–12 dia high strength strand
Weight of structure 13 kgs/sq metre.

Figure 15 Design Example

Members sizes and overall weight of the structure are also shown. These results are discussed more fully later in the section on costs.

The computer programs used for this analytical work were ELSO and SPACEGASS. Both are capable of analysing structures whose behaviour is non–linear, which have tension–only members and in which second order (deflection) effects are important. The data preparation and processing time for structures of this type is quite high and much of this cost can be avoided for concept studies by analysing an equivalent two dimensional module of the structure envisaged ie. a two dimensional truss of the type previously described. For simple structures, such as a barrel vault, this has been found to give acceptably accurate results. For less regular structures care must be taken to ensure that the two dimensional module will provide realistic, and preferably conservative, results. The assumptions about the boundary conditions of the two dimensional model must also be achievable in the full three dimensional structure and be reflected in any cost study, an example being, the perimeter tie for a dome structure.

Concept studies using this technique have been used for several roofs and it was also used for a tender design for a roof over a water reservoir.

It is intended that routines for generating the input data for these structures will be developed and three dimensional analysis will then become a simple process.

6. ASSEMBLY AND ERECTION

It is envisaged that the system will be most cost competitive for roof structures of medium to very long span. For these the structure and cladding are often at a considerable height when in their final erected position. The cost of assembly at height is already high and it will probably tend to increase in the future as safety requirements become more stringent.

The response of the industry to this trend has been to devise methods of assembling the structure, cladding and services on the ground and then raising the complete assembly into its final position by a variety of techniques. These include raising large assembled segments into position by crane, by jacking up on columns or strategic application of jacking forces to the structure.

The erection of MacroSpan uses the last of these techniques. The assembly and erection of the structure is executed by the following procedure which is shown in Figure 16:

(a) Assemble structure on the ground with a slight precamber.

(b) Apply a proportion of the prestress to the main tendons as determined by the requirements of the design, restraining the perimeter of the structure against uplift as required.

(c) Install cladding and services should the shape of the roof permit this.

(d) Draw the sides of the structure inwards, raising the interior of the structure to its final form and increasing the prestress in the structure to its final design value in the process. Anchor the support points.

The sides of the structure are drawn in by jacking against anchored points or by pulling one side against the other.

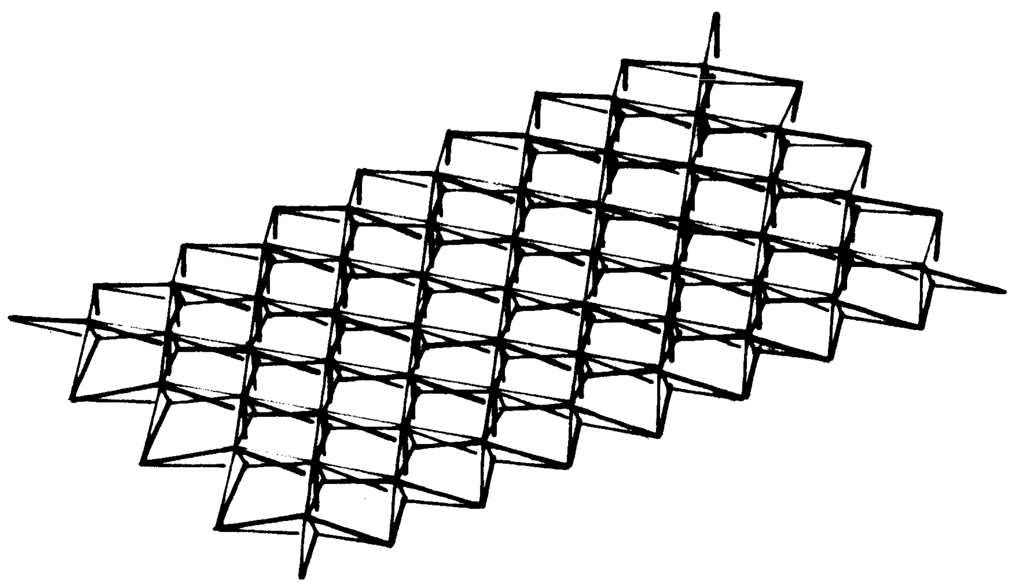
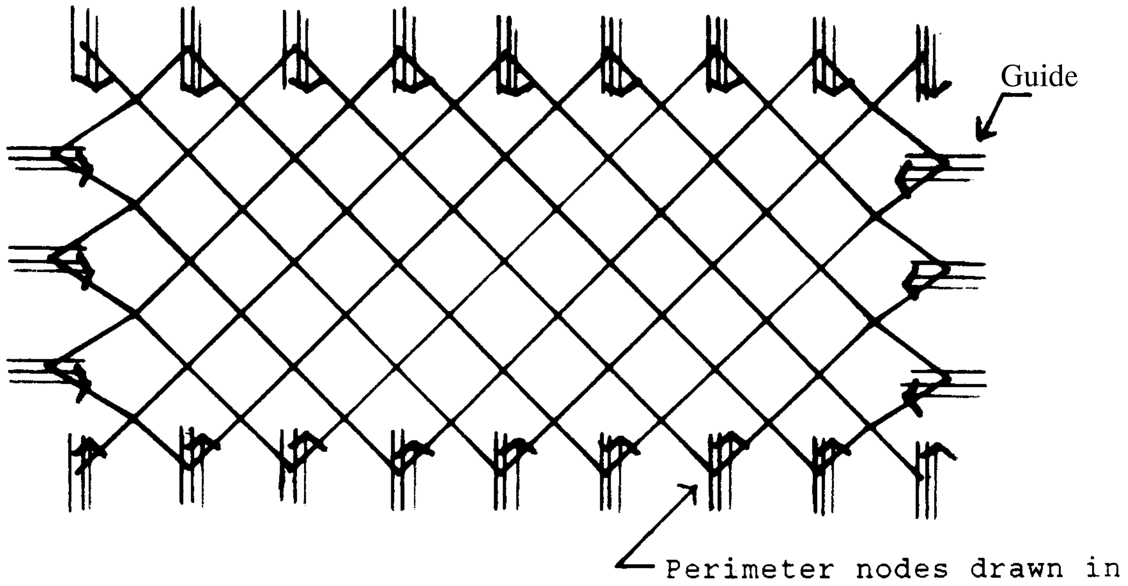


Figure 16 Barrel Vault Erection – Isometric of Assembly on Ground



Plan View

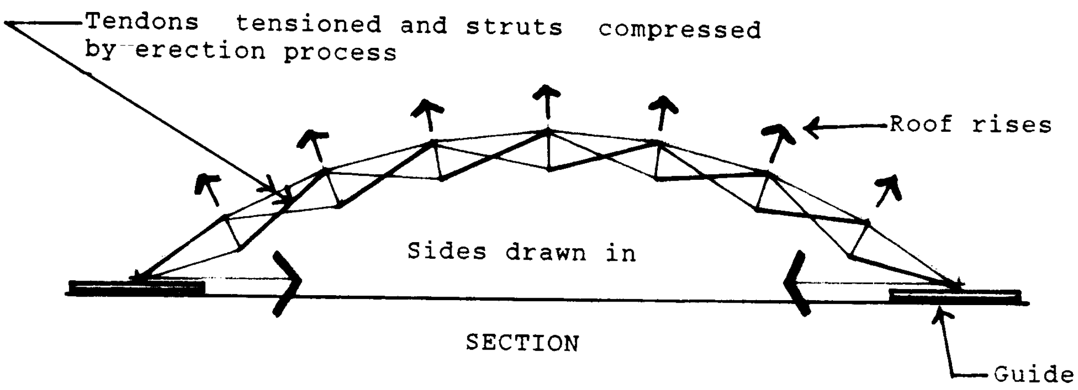


Figure 16 (Cont.) Barrel Vault Erection

The main tendons are stretched by the erection process resulting in prestress being induced into the main tendons, the main struts and the radial ties.

As mentioned in Section 3 the tension loop around the structure must be closed and this can be done either by introducing ground ties linking one side of the structure to the other, ground anchors or other means. In the case of a dome a perimeter tie will suffice.

The timing of the installation of the cladding and services will depend upon a number of factors but a deciding one will be the shape of the roof. For singly curved roofs it will be possible for many types of cladding to be installed prior to erection but for doubly curved roofs the erection process causes rotations in the structure in the plane of the roof, thus precluding this technique. In this case the cladding, which will probably most often be a membrane, is installed after the erection of the structure.

7. MATERIAL WEIGHT AND COST

Most of the investigation on material weight and cost of construction of MacroSpan has again centred around the barrel vault in Figure 11 and the results are shown in Table 1.

	MacroSpan	Trussed Arch
Material weight	13 kg/sqm (CHS struts) 9 kg/sqm (composite struts)	11 kg/sqm
Erected cost	$3000 / tonne (CHS struts) $ 39 /sqm (CHS struts)	$ 3800 /tonne $ 41 /sqm

Table 1 70 Metre Barrel Vault – Costs

The figures in this table are based upon the use of simple tubular steel struts. The table shows that significant reductions in the weight of the struts could be achieved by using a composite strut of the type shown in Figure 5 although, as previously discussed, they would probably not be cost effective for this medium scale structure.

Table 1 also provides a comparison between the weight of MacroSpan and that of some other types of long–span systems which were investigated for the barrel vault.

The differences between the figures are thought to be too small to be conclusive. It is believed, however, that this structure is at the lower end of the cost effective span range of MacroSpan and that it will mainly prove its cost effectiveness for very long–span structures. For these the arching principle will show its real advantage and the adoption of composite struts, incorporating high strength steel, will prove a real saving in terms of the reduction in self weight of the structure. This becomes a significant factor as the span increases and the self weight of the structure becomes a higher proportion of the total load applied to it.

Whilst the cost of MacroSpan has been discussed in qualitative terms with two major structural steel fabricators, there have thus far been few opportunities to undertake detailed cost analyses.

The one exception has been the roof over the water reservoir, previously referred to, which spanned 78 metres. The cost of the erected steel structure was tendered at $3,000 per tonne. This compares with $3800 per tonne had the structure been a conventional arch. The result of the application of these figures is also shown in Table 1.

Not too much store should be set by this comparison, however, it does demonstrate that even for medium span structures MacroSpan is quite competitive and it is likely to be more so for longer spans.

8. CLADDING

Cladding can be either conventional metal deck on purlins or fabric membranes as shown in Figures 17 and 18 respectively. The metal deck would normally be used on one way curved roofs and installed prior to erection. In this case the cladding bends during erection and provision must be made for movement between the tendons and the purlins, as shown in Figure 17.

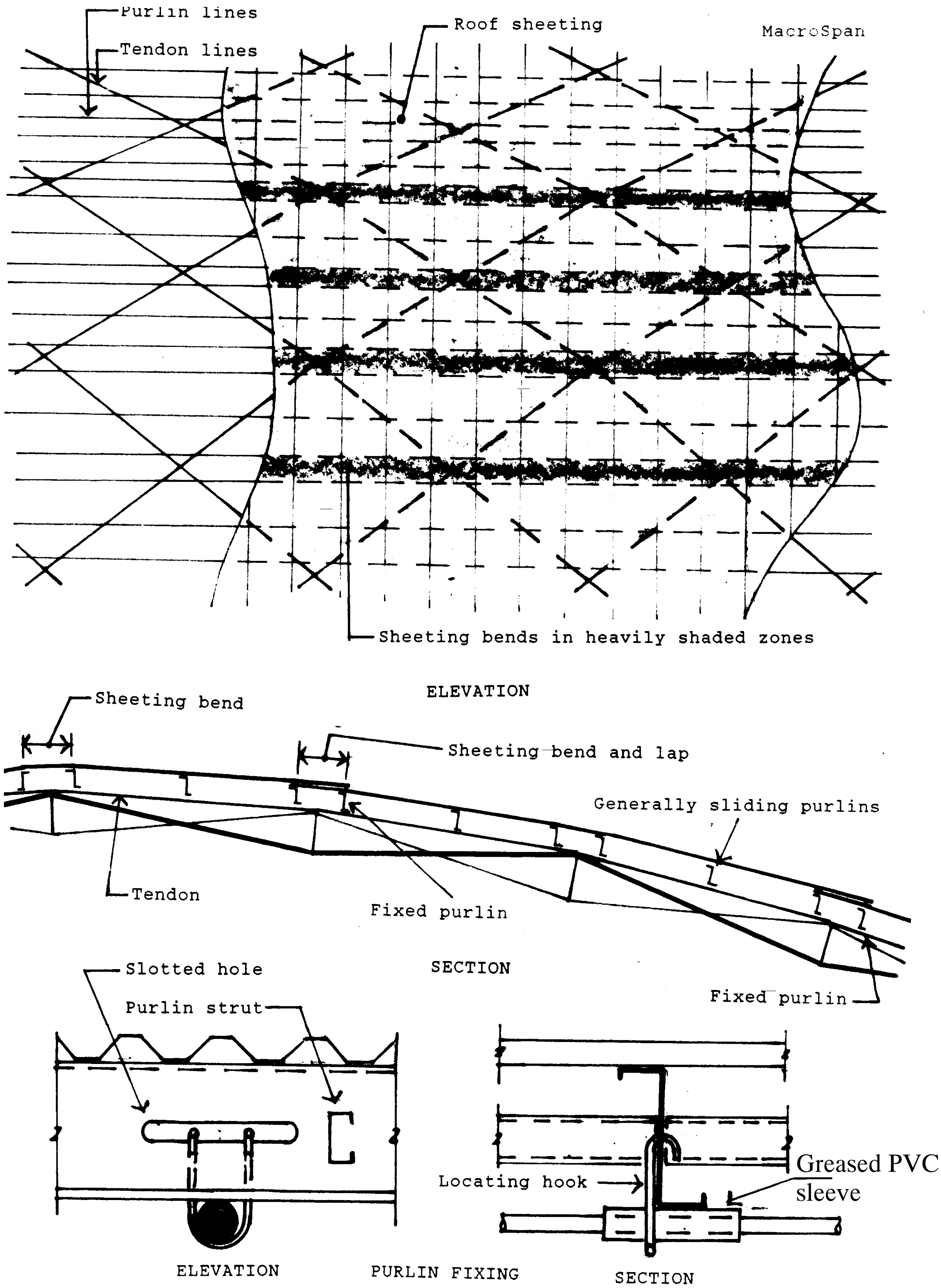


Figure 17 Cladding Option – Purlins and Metal Deck

The fabric membrane cladding could also be used for one–way curved roofs and it would appear to be the most appropriate cladding for two–way roofs, being installed after erection. Note that MacroSpan naturally forms saddle surfaces between tendons after erection which is essential for membranes.

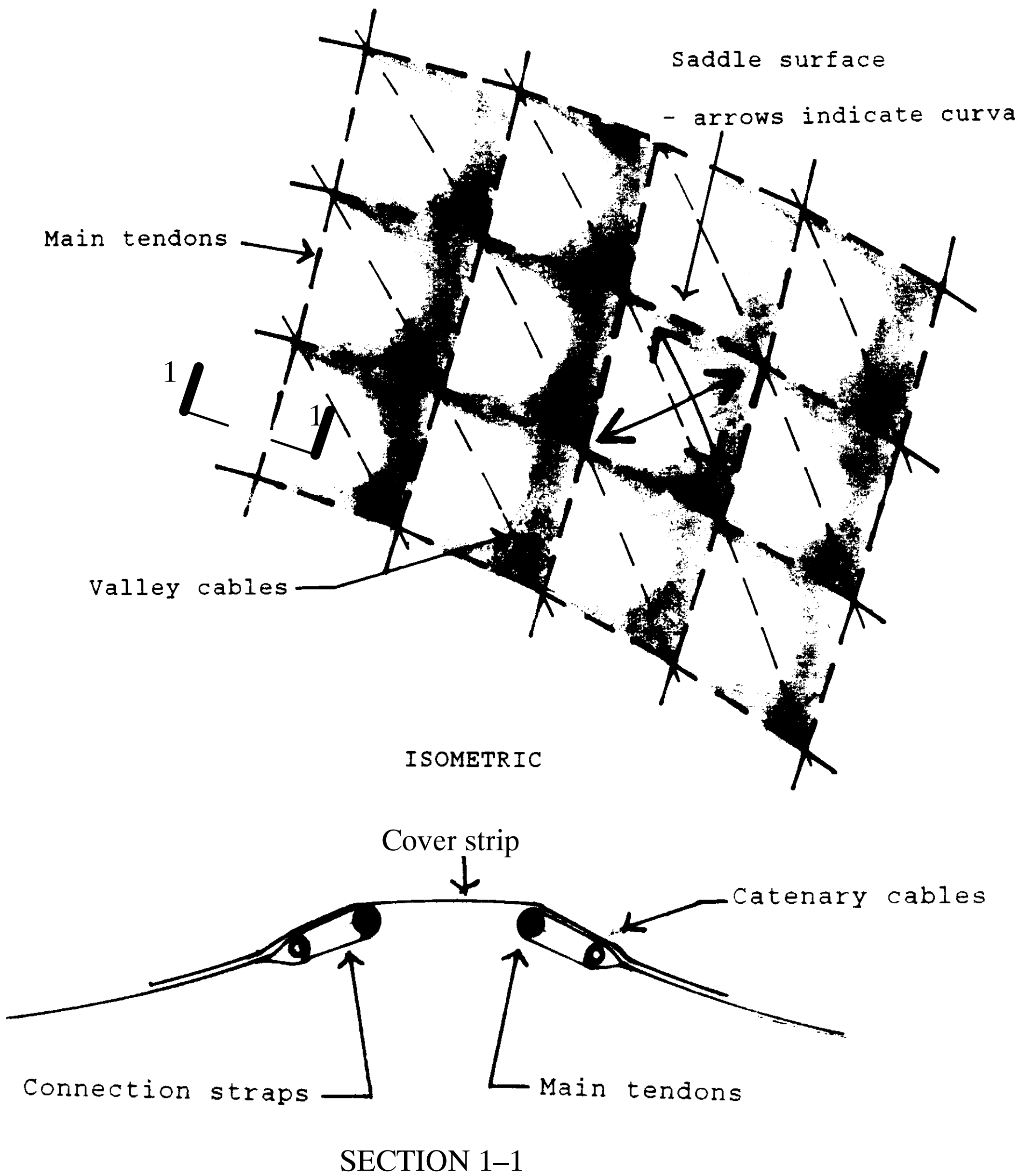


Figure 18 Cladding Option – Membrane

9. APPLICATIONS

The characteristics of MacroSpan give it quite a wide range of applications. These characteristics are:

- Demountability and transportability
- Ease of erection without the need for heavy craneage
- Repetition and simplicity of assembly
- Long spanning capability

Applications envisaged are:

- Roofs for sporting facilities including major sporting stadia
- Exhibition buildings

- Industrial buildings
- Aircraft hangars
- Roof coverings for water reservoirs
- Demountable/mobile shelter for agricultural, military and humanitarian use.

MacroSpan can also be used for its high–tech image in architectural applications. It was recently incorporated into a schematic design for the conversion of a large historic railway maintenance shed into an exhibition/convention centre.

10. CONCLUSION

In this paper the concept of MacroSpan and its construction details have been described. Its performance characteristics were explained in qualitative terms and approximate material use and cost data were also provided. The likely uses for the system have been discussed.

Future applications of the system will be based largely upon its flexibility of form and its economy over long spans. Its architectural qualities will probably be of varying appeal.

It is likely that MacroSpan's future development will occur in two areas, the first being construction and erection details for specific applications. The second area will be conceptual development in which it is envisaged that the system will evolve back towards its origins in Tensegrity.