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Straight Tensioned Cable Roof Structures

Structure de câbles rectilignes en tension pour des toitures

Dachtragwerke mit vorgespannten geraden Drahtbündeln

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SUMMARY

The use of straight tensioned cables with fabric of foil cladding can result in translucent roof structures with useful environmental properties at very competitive costs. This paper describes two projects designed on this principle one of which is now under construction.

RÉSUMÉ

L'emploi de câbles rectilignes en tension, supportant des toiles, peut contribuer à des toitures translucides aux propriétés intéressantes et à des prix très compétitifs. Ce document décrit deux projets conçus selon ce principe, dont l'un d'entre eux est actuellement en construction.

ZUSAMMENFASSUNG

Der innovative Einsatz von Gewebefolien in Verbindung mit Seiltragkonstruktionen für transparente Dachtragwerke ist als eine sehr ökologische Tragwerksoption anzusehen. In diesem Beitrag werden zwei Projekte beschrieben, bei denen diese Tragwerksvariante eingesetzt wurde. Eines dieser Projekte befindet sich zur Zeit im Bau.

INTRODUCTION

The now traditional constructional systems for cable roofs use one set of cables to carry uplift loads with a second set of cables to carry down loads. These cables are either arranged at right angles to each other to form a surface with anticlastic curvature, or the cables can be separated vertically as in a cable truss. There are considerable advantages in using single straight cables, particularly in association with fabric or foil cladding.

> Compared with a two way cable net, one set of cables is eliminated along with the cross clamps and the anchorages.
>
> Whether the load is upward or downward the cable tensions are in the same direction which can be a great advantage if the tensions are taken by a funicular arch or ring beam.
>
> Connections to the foil or fabric cladding can be greatly simplified.

Taken together these benefits can result in very economical roof structures. This paper describes two such designs, one of which is now under construction.

Harlow Velodrome

The requirement was to provide a 500 metre oval covered cycling track with seating for some 3000 persons. The velodrome would be used by the existing cycling club for training and inter-club competitions. Occasionally international meetings would be held. The potential income from this activity was low, but additional income could be generated by using the hall for other sports events (e.g. tennis) and for music concerts. Three tennis courts could fit in the central area but the track caused problems with seating and access for concerts. The facility was to be jointly funded by the cycling club who were to gain some capital from the sale of their existing site and the local authority. For the facility to be viable the capital costs had to be minimised.

The proposed structure was a cable roof with straight cables anchored to a horizontal ring beam and supported by a funicular arch (Figs. 1 & 2). The ring beam was 90 metres by 120 metres to be constructed in precast concrete. It sat on top of a series of A-frames, the sloping leg of which carried the seating outside the cycle track. The cable forces were largely taken directly into the A-frames, with some residual compression and bending in the ring beam. The supporting arch was a four chord tubular steel truss spanning 160 m on to concrete abutments which were tied together by a ground beam.

The cable lines were at 10 metre spacing, the longest cables being 50 metres long. They were designed to be prestressed to 50kN under zero external load conditions. Each cable line consisted of a 42 mm diameter wire rope cable. Under extreme loads the tension in the longest cables would rise to 500 kN.

Because the cables were designed as prestressed even under zero load conditions they are able to provide lateral stability to the spine arch. This resulted in considerable economies in the design of the arch.

The cladding was to be PVC coated polyester fabric panels. The panels were double layer, the outer layer of type III PVC/PES cloth being prestressed and carrying the loads. The inner layer of a lower strength PVC/PES cloth acted as a liner which provided an air gap and would be unstressed. The two layers were to be made up together and finished with a roped edge which slid into grooved aluminium extrusions on the cable lines.

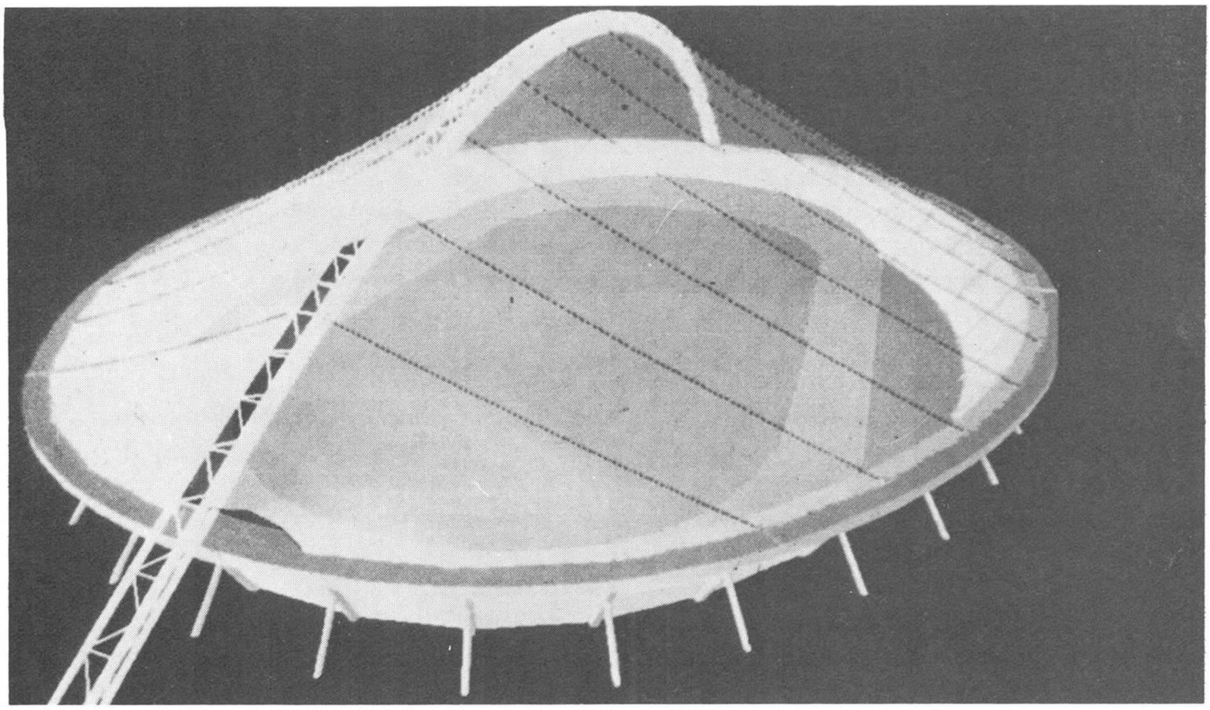

Fig. 1. Computer model of Velodrome

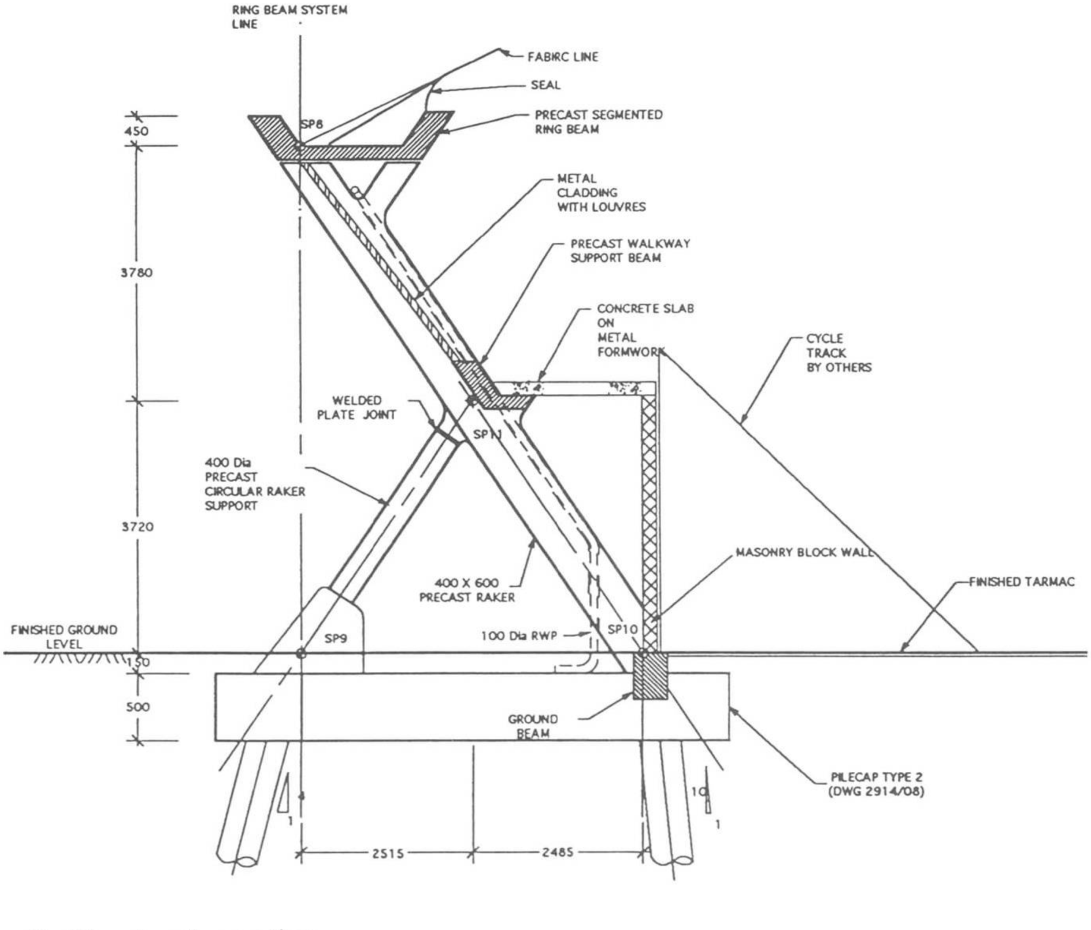

Fig. 2. Structural section

Tennis Halls

The second structure is a 10 court tennis hall for a tennis and health centre with a plan area of approximately 6000 square metres. Again there was a strong financial pressure to minimise costs. In this case the structure was being compared with standard portal frame halls normally provided as design-build packages. The objective was to use as cladding triple layer ETFE foil inflated cushions. This roofing system offers a wide range of translucencies, together with a reasonable degree of insulation by virtue of the triple layer construction. The foil cladding is relatively expensive and the system could only be made viable if the structure costs were minimised.

The cushions are supported on pairs of 18 mm diameter cables at 3 metre centres supported from a longitudinal ridge cable which is in turn supported by opposed external masts and ties (Fig. 4). Each of the two ridged structures is 78 metres x 36 metres, separated by a steel portal frame spine. The entire structure is stabilised via a system of external ties and ground anchors. Under permanent load conditions the parallel cables are stressed to 20-50 kN, rising to 100-150 kN under applied load.

The ETFE foil panels are approximately 3 metres x 20 metres. The outer and inner layers are 150 µm and the middle layer is 30µm in thickness. The cushions are pressurised to 300 to 400 Pa. This pressure causes the initially flat foil to stretch and curve out so that the cushions have a rise of about a tenth of the span. In this condition they are able to resist full wind and snow loading. The foil panels are connected to the cables via an aluminium extrusion clamping system which allows for full movement of the cables under wind loading and thermal variations (Fig. 3). The foil edges at top and bottom are terminated on aluminium edge channels which house air supply hoses. Differing from the connections of foils in rigid frame roofs, the details for the foil to cable connections have been designed to take into account the movements of the cables. Rotations in the end connections to perimeter steelwork necessitate the use of sliding panels at the edges to accommodate for in-service movements and easy installation.

ETFE foils have been commercially developed for construction purposes over the past 15 years, primarily in Germany and the UK. The leading manufacturing firm is Vector Foil Gmbh. Buro Happold have been involved in developing lightweight foil enclosure designs since the early 1980's when cushion construction was first considered for several large enclosure projects including the design of a covering for a township in Northern Canada. Currently, foil cushion roof are being used in applications where controlled environments, but high sunlight transmission is desirable, such as sporting halls, swimming pools, or greenhouses. However, advances in manufacturing processes, detailing and general acceptability have opened up wider possibilities in the use of foil roofs. Due to their insulation and high light transmission properties, ETFE foil cushion constructions have been increasingly introduced as economical alternatives to glass panel systems and planar glazing for roofing enclosures such as atria, sports halls, swimming pools and retail areas.

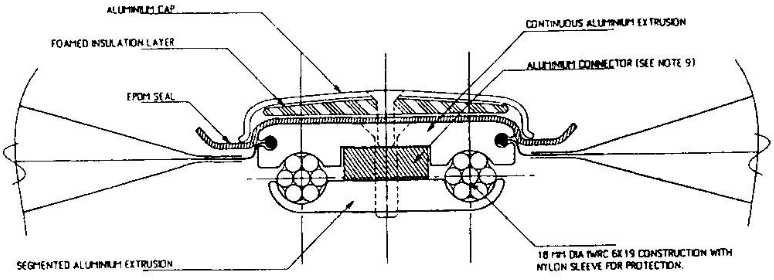

Fig. 3. Flexible extrusion connection detail

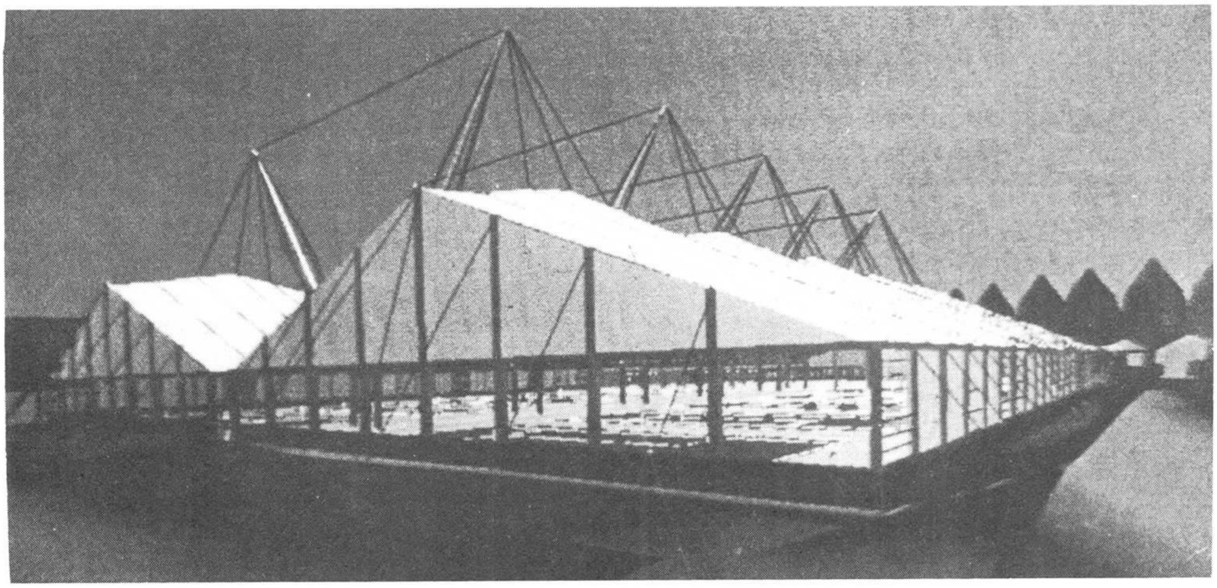

Fig. 4. Computer modelling of tennis halls

Analysis and Design Considerations

Under static load the cables stretch with increasing tension which allows the curvature to increase until equilibrium is reached. The deflections under peak loads may be a metre or more. To calculate the forces in a single cable it is possible to solve the nonlinear equation by hand or with a calculator. However it is easier to use a nonlinear computer program such as TENSYL which gives the forces in all the structural members. Such a program can also be used for the form finding stage in which the geometry of the structure is optimised.

Of greater interest is the behaviour under dynamic loads as from wind. For small oscillations where the cable tensions do not vary significantly the natural frequency $= \sqrt{(T/w)}/2*L$. For the tennis hall example this results in a frequency of ≈ 3 Hz if w is taken as the self weight of cables, clamps, foil, etc. At this frequency there is little energy in the wind. The response is affected by damping from the added mass of the air, from acoustic energy given to the air at a distance from the roof, and from the material properties of the cables and cladding. The result of this is that a resonant response should not occur. This concurs with the experience of similar flat tensioned structures e.g. marquee tents. However the roof will move a lot and this must be taken into account in the detailing.

As indicated above, the structural form resulting from the adoption of straight cables is simplified when compared with alternative two-way cable nets. In a two-way cable net the formfinding is a complex iterative process, in which the individual link lengths of the net must be adjusted to find an equilibrium form. In the proposed forms using prestressed straight cables, the cable forces dominate the resulting form and allow rapid determination of the shape of the roof given suitable boundary conditions.

In the case of the Velodrome, the A-frame, ring beam and supporting arch define the roof enclosure and the cables are essentially slightly curved generators of the form between these boundaries. Both vertical and horizontal curvatures are controlled by the amount of prestress in the cables. The fabric acts primarily to distribute loads to the main cables, which can lead to high lateral forces in the event of failure of a single panel of fabric. In roof forms such as this it is also possible to extend the structural system such that the fabric panels are retractable along the line of the main cables (Figs. 5 &6).

In the case of the Tennis Halls roof, the central spine and external tie-backs define the boundaries. The roof shape is controlled by the interaction of the single ridge cable and its supporting mast with the parallel cables at 3 metre centres acting as stringers for the foil cushions. The inflated cushion system results in high lateral forces at the clamped edges, which must be considered, particularly in conditions where the loading is not equalised on both sides of the main cable.

Both of the above structures have been successfully assessed and analysed using the TENSYL computer software developed by Buro Happold for the design and patterning of tensioned fabric structures. This integrated system ensures that the designer has full control of the analytical model and the system geometry at all stages of the design and fabrication processes. The provision in TENSYL of cable elements under force control (i.e. the behaviour of the cable is governed by a defined tension overiding its elastic properties) enables rapid assessment of the effects of changes to the prestress levels in the cables. The final scheduling of cables and boundary geometry is aided by the facilities provided in TENSYL for the calculation of linear and angular geometries.

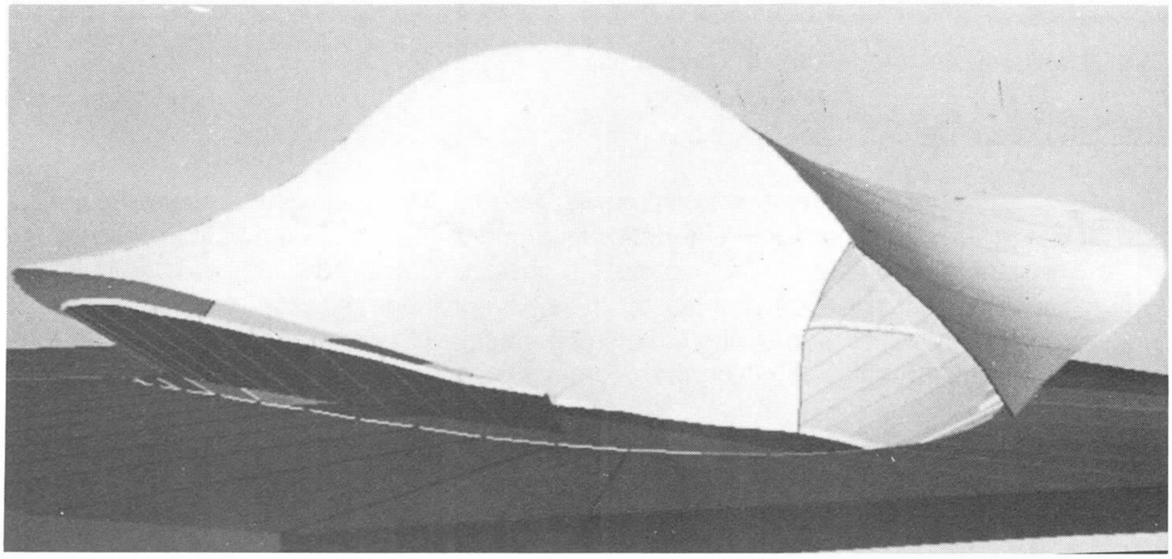

Fig. 5. Computer model of Stadium Roof with fabric closed

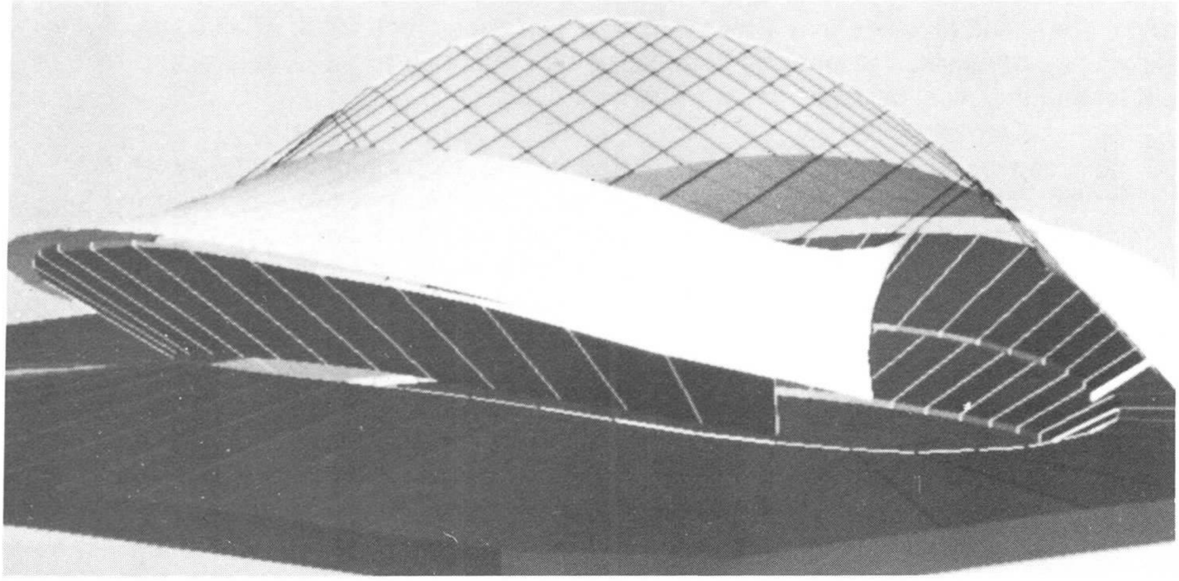

Fig. 6. Computer model of Stadium Roof with fabric retracted