THE INTEGRATION OF LARGE FABRIC STRUCTURES WITHIN BUILDING PROJECTS INCLUDING THE SIGNIFICANCE OF DESIGN AND PROCUREMENT METHODS
Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

1. INTRODUCTION

The fabric structures industry has always been interesting because of the spread and diversity of the "engineering" embodied within the design and construction of such structures.

Contractors and consulting engineers are distinct commercial entities yet both share a common culture of being "constructors". Both employ imagination and skill and a problem solving approach, as well as applying appropriate degrees of engineering rigour in the execution of their work.

In the technical sense we share common thought processes and have created similar "intellectual tools" directed towards broadly similar goals.

In this field "design" must always embody the means of making and building- essentially a design has to be prestressable. This truth pretty much runs all the way through the design process until it finally informs the details of boundary connections.

The scope of "engineering design" might briefly be stated as;

1. Developing a design concept; defining a physical configuration of elements, materials and their strength and stiffness properties, element sizes; defining the connections between all elements.

2. Determining how it is to be built - establishing a sequence of assembly and the step by step means of obtaining the specified prestress distribution in advance of fabrication.

3. Calculating unstrained dimensions for fabrication - cutting patterns, nodal geometry, shop drawings.

Broadly speaking item 1 is more often performed by consultants, sometimes contractors, and items 2 and 3 broadly by contractors though there are some highly effective consultants working directly for contractors.

Our own work tends to concentrate, though not wholly, on item 1 where we are integrating membrane enclosures into building developments as the following examples will show and where choices of design and procurement strategies apply according to circumstances.

Fabric structures are essentially a constant thickness surface typically less than 2mm (and with significant limitations on reinforcement) which are given the capacity to carry loads by virtue of the choice of surface shape and their large deflection behaviour.

Whilst being intrinsically light in weight they do however deliver large forces to whatever they are anchored to. Membrane tensions of 20-30kN/m are common in large permanent structures. Therefore "design" must comprehend and include supports as an essential part of the system.

In relation to using textile membranes as an enclosing element within a building development we see the virtues of containing the membrane's tension field within a closed system in that large "stray" tensions are diminished in their effects on the supporting building and small deflection continuous boundaries simplify the enclosure detailing.

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

This kind of approach however does demand greater degrees of certainty of obtaining specified prestress within a far less variable support geometry than "open" tent structures enjoy. There is within this category the potential for the supporting frameworks to be prestressed to varying degrees within themselves. This is sometimes exploited architecturally and can involve structural interaction effects between membrane and beam elements that need explicit numerical modelling for structural frame justification, membrane cutting patterns and installation method.

Design and procurement strategies of course have to appropriate to the project brief whose primary purpose might be:

earliest start on site, or
lowest price, or
maximising client operational benefits, or
elimination of technical/time/cost risk.

2. YKB OPERATIONS CENTRE, GEBZE, TURKEY

Figure 1 YKB view along street

Yapi Kredi Bank is one of the largest private banks in Turkey. In 1993 it was outgrowing it's city office block and decided to move it's data centre and major operations to a site 50km SE of Istanbul. The bank appointed Arup MMLS as prime agent responsible for project management, development of brief, design and cost control. Troughton McAslan and Metex joined the team as Architects.

The Bank wanted an exceptional building - breaking the mould of typical city centre offices. It needed to be adaptable, capable of phased extension and IT/Comms orientated. TMA's master plan outlined three stage of development, the first two of these, amounting to 44000m^2, are now complete and occupied. Their design has drawn on traditional Turkish planning in the use of courtyards and covered streets and consists of a cluster of 35m square three storey open plan blocks on rising ground.

The streets link the individual blocks together and whilst serving as circulation, are also focuses for social activities being furnished with cafes and tropical plants. They are enclosed

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

with textile roofs (PTFE/glass) and glazed end walls - both integrated into the enclosing skin of the whole complex - and so enabling the streets to be a climatic buffer zone between the extremes of inside and outside temperatures. The streets are naturally ventilated in summer and heated to 17^{o}C in winter using convected heat delivered through trenches at street level.

With regard to the seismic nature of the area (corresponding to UBC Zone 4) it was important that both the roofs and walls should accommodate the independent sway movements of the individual buildings (± 60mm in X and Y directions).

Figure 2 YKB view of glazed end wall

Design work initially considered each roof and wall as stiff flat planes attached to one building but on the other free to slide in X and Y so as to avoid structural coupling. However as this type of arrangement was examined concern developed over the architectural legibility of the junctions between glazed wall, building facade and roof. Was there an alternative to sliding movements? Thoughts therefore turned to the obvious advantages of a 3-pin arch and ultimately progressed onto that of the 2-pin arch. Displacement of buildings relative to one other along the streets causes a 'racking' action on plan and so a roof construction with low shear stiffness and geometric flexibility was desirable and provided part of the justification for using a textile membrane.
The arches were initially thought of as frequent parallel arches over which the membrane passed. However, pairing arches together into a 'lemon-wedge' shape enabled the roof and the glazed end walls to have a common curved boundary.

The form of the end arches has its origin in the search for ways of enclosing the streets at the 4-way junction with the stair towers where roofs sometimes arrive at different levels. The solution involves a third arch laid in a horizontal plane linked to the outer arch using inclined tubes which double-up as glazing bar supports. These were set out on the surface of an elliptic cylinder to support framed glass panels.

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

The membrane tensions across the street go directly onto the buildings via external rigging screws. The membrane is connected only to the end arches and simply bears down over the intermediate ones.

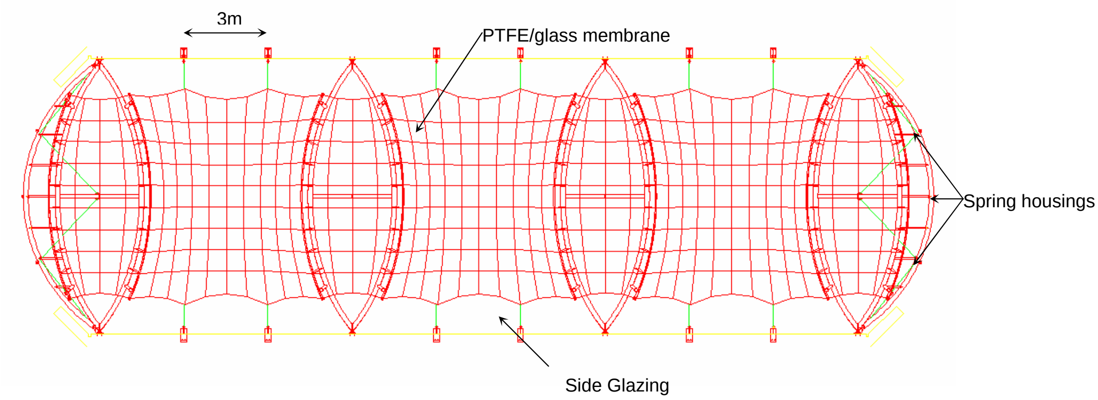

Figure 3 YKB Plan of lightweight street roof

The intermediate arches are stabilised longitudinally by means of cables connected to a ‘Y’ shaped lever projecting down below the axis of the arch pivots to provide a simple counterbalance. At each end these cables fan out to react against the horizontal end arches, this arrangement smoothing out bending moments around the arch.

The longitudinal ties are modestly prestressed to 15kN. In the event of the buildings moving apart, the distance between the crowns of the end horizontal arches reduces by an amount significantly greater than that provided by the prestress strain in the longitudinal tie cables. To compensate for this, and so avoid dynamic "snatch" loading of the structure, pre-compressed springs are provided at the ends of the cable system. The springs are stacks of disc-springs tailored to give an appropriate stiffness and range of displacement and are contained within sleeves set into the arch tube itself. In normal circumstances they have no influence on the stiffness of the longitudinal tie. They come into play with extreme building movement whilst maintaining a small residual tension in the cable.

Conversely as the buildings move towards each other the force in the longitudinal tie system increases. As the buildings approach what is perceived as an ultimate state of movement the forces in the tie system become large enough to threaten rupture at points in the arches and Y frames. To protect against this a ‘fuse’ is incorporated at mid-length in the longitudinal tie which will yield and thereby reduce force in the system.

The glazed walls are somewhat simpler in action but again use the 2-pin arch as the means of absorbing the imposed movements of the adjacent buildings without recourse to movement joints.

The seismic movements of the buildings cause change in shape of the hoops and additional bending. Another consideration was the general warping affect of the glazed surface as a result of the edge displacements increasing from zero at the bottom to maximum at the top. This distortion is absorbed within the elasticity of the sealant joints in the glass.

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

The roof steel and membrane constitutes an interactive system. Similarly, but to a lesser extent, so do the glazed walls. In these circumstances designers generally would want to bid the two as a single system with a single contractor responsible for the complete roof.

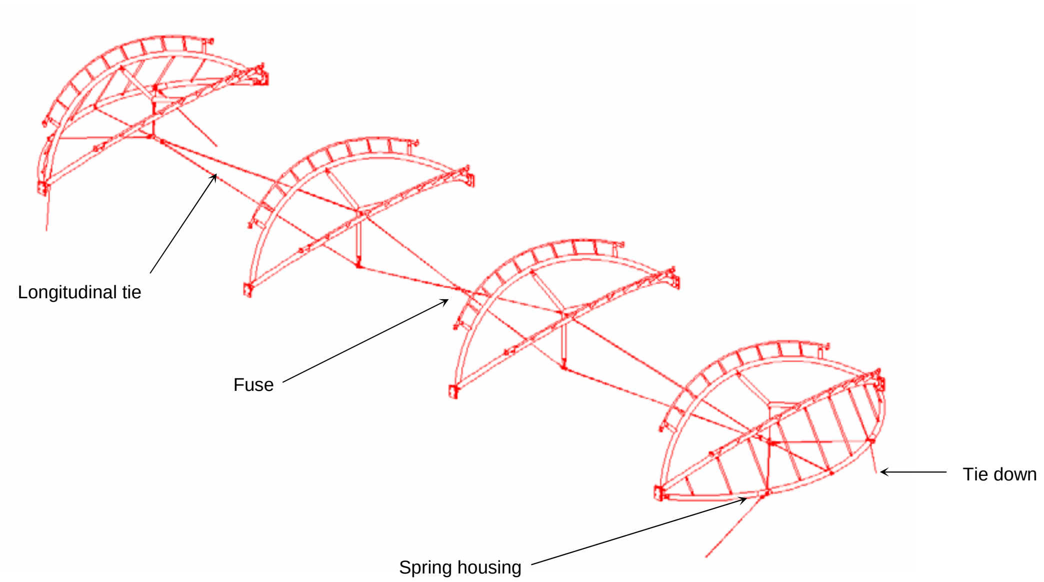

Figure 4 YKB perspective of roof truss system

However, it was foreseen that commercially and technically the best bids would be obtained from three separate trade contractors, which indeed was the case. Consequently the bid drawings and specifications were detailed to a high degree with the requirements at interfaces clearly defined. This included the results of numerical modeling in a two stage construction process for the roof including anticipated movements and target element prestress values.

Comment:

The flexible closure pieces that had to take up movement between roof, end wall and side glazing were specified by performance criteria which included movements during normal loading events as well as seismic ones.

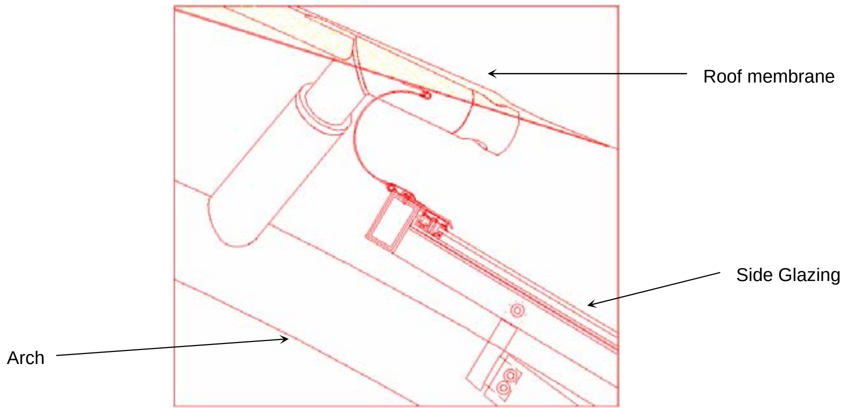

Figure 5 YKB closure detail

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

This strategy with the bid documents worked well in that value for money was obtained. The Construction Management system of site administration by Baytur was also effective.

3. BUKIT JALAL - STAR LRT STATION (KUALA LUMPUR)

Our client for this project is Taylor Woodrow Projects who, as part of a design/build/operate consortium, appointed ARUP as lead designers for all the civil, structural, building and M&E works involved in a 12km extension to the STAR LRT system in KL.

40% of the track is elevated with the remainder at grade. Arup in conjunction with Tay Kiam Seng of Arkitek Kitas designed 11 new stations along the route one of which - Bukit Jalal - serves the new stadium for the 1998 Commonwealth Games. Track and platforms are 10m above grade. Ground conditions are poor with the station's R.C. framed superstructure supported on piled foundations.

A pure "tent" roof supported by masts and tie-backs would have posed serious practical issues as the overturning moment at foundation level would have been about 1000 tonne metres per 10m run of roof.

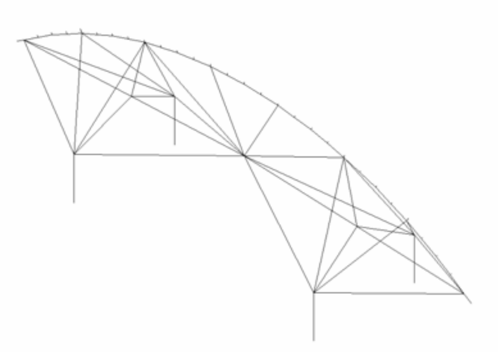

Figure 7 KL frame isometric

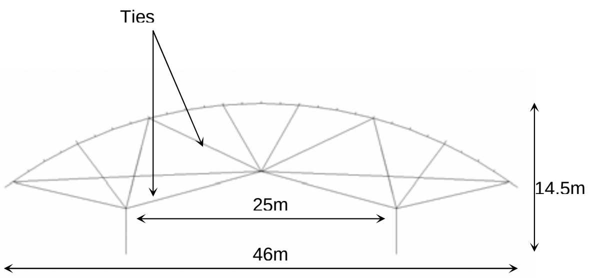

Figure 6 KL frame elevation

This, combined with the importance of construction time and cost, led us to develop a simple repetitive PVC/PES membrane stressed over an arch framework. An important feature of such a system is that the in-plane membrane tensions are largely balanced out within the framework itself at roof level thus avoiding large overturning moments and therefore enabling simpler foundations to be used. The roof is 100m long x 46m across and rises to 14m above platform level.

The framework is stiff enough in itself to avoid structural interaction effects with the membrane, which can complicate installation and stressing. The arched roof shape is also consistent architecturally with the appearance of the other, albeit smaller, stations along the route.

Architectural interest was introduced by vaulting the roof elevation longitudinally. This was achieved by setting out the primary trussed arches on radially inclined planes and is also reflected in the changing height of the supporting columns above platform level. Nevertheless considerable geometric repetition of membrane panel and truss framework has been built-in and a steelwork weight of 32kg/m^2 of plan area has been achieved. Prestressed tie-rods have contributed to this relatively low weight by reducing the buckling length of 46m

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

long bottom chord of the arch truss. They have also been used as tensile shear bracing, again, prestressed.

Selected trade contractors were invited by Taylor Woodrow Contracts to bid on the basis of either individual steel and membrane packages or a combined package. Consequently detailed tender drawings and specifications were prepared permitting this strategy. These gave specific member sizes, membrane strength, detailed geometry of steel and membrane, characteristic connections of all primary elements including membrane tensioning and sealing, membrane/steel interfaces, rainwater disposal, lighting support and electrical supply.

The contractors were to be responsible for completing the detail design according to standards and criteria given in the OAP specification and drawings. In the case of the membrane package, the trade contractor was responsible for continuing the development of the enclosure system and integrating into this the tensioning system for installing the membrane prestress. As a procurement tactic this can open the way to design development giving cost and operational benefit to the client/user - which is indeed what happened in this instance.

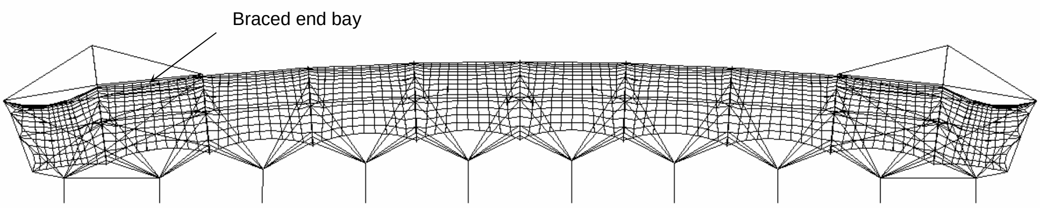

Figure 8 KL long elevation

Landrell, the trade contractor, opted to divide the membrane panels between individual trusses into two parts so as to splice and prestress them individually against a ridge beam introduced specifically for this purpose along the longitudinal centre line of the roof. By this means the effects of future panel replacement on the operation of the train system were minimised yet further.

The nature of the OAP drawings and specification enabled the client to agree ± cost adjustments to the two individual packages.

The Malaysian steel subcontractor, Cahayas Luas, was responsible for the detail design and justification of the steel to steel connections. This work was contracted back by them to the author’s team in London. We also prepared the installation analysis for the introduction of prestress into the steel system. This was done by disassembling the computer model of the whole structure at prestress, including the membrane, in a series of steps, which were the reverse of the intended construction process.

This type of work is always very interesting as it involves presupposing a series of discrete steps (which must of course be practically realisable) and then testing these by numerical means. Iteration of the process can eventually lead to practicable solutions in dialogue with the contractor. The practical technique of installing and verifying element prestresses always needs to be as insensitive as possible to fabrication and construction tolerances. On this project the tie-bars stabilising the mid span node of the truss were stressed by jacking pairs of

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

columns together across the track with a known force. The bars were then inserted and load transferred onto them from the jacks.

Due to a difference in the configuration and stiffness of the two end trusses compared with the seven internal ones, a two-stage jacking process, applied to all columns simultaneously, was found to be necessary. Four other categories of tie-bar were installed in symmetric patterns with checks carried out in situ using site calibrated torque wrenches.

Figure 9 KL view along platform

4. DYNAMIC EARTH CENTRE - EDINBURGH, SCOTLAND

This building is to house an interactive museum of earth sciences and is due for completion during 1999. It is situated on the outskirts of the city close to Holyrood Palace and a volcanic outcrop known locally as Arthur's Seat. The form of the roof in some way reflects the latter. The Architect is Sir Michael Hopkins & Partners.

The roof is 75m long x 33m wide and rises to a clear internal height of 11m. It has a surface area of 2800m^2 and the membrane material is PTFE coated glass. The roof is enclosed by a free standing glass wall whose height varies from 4m to 7m as it translates round an ellipse on plan. The wall is set inboard of the roof’s cabled edge to create a covered ambulatory around the whole building.

The roof is to be supported by three storeys of framed insitu concrete construction. This is currently under construction by trade contractors operating under a Construction Management form of contract. Birdair Inc are the trade contractor for the roof. For programme reasons bids were invited before detailed engineering design drawings were available. Membrane Contractors were invited to bid against architectural drawings, an engineering specification and material quantities.

The roof is a large structure with a fairly high degree of interaction between the membrane surface and flexible steel ribs that are suspended from tall masts. It is therefore worth looking at the nature of the roof structure and how the engineering tasks have been shared between OAP and Birdair Inc.

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

The steelwork is to be fabricated to a specified (and unstrained) geometry. As the membrane is tensioned it applies force to the steelwork which causes strains and therefore deflections to occur. The surface geometry of the membrane at the specified prestress has therefore to be compatible with the deflected geometry of the steel. Appropriate analytical tools are employed by us to do this. This is necessary for a satisfactory structural analysis/justification to be made for all the structural elements and connections in the roof's completed state, as well for calculating the shape of the membrane surface which Birdair will replicate in the process of calculating their cutting patterns.

Similarly the effects of a developing stress field in conjunction with the flexibility of the steelwork have to be taken into consideration in planning the erection/assembly/prestress process step by step. Birdair's method statement for the erection of the roof will be informed by the results of their computer model of the structure. The purpose of this work is to confirm the stressed state of all membrane, cable, rod and steelwork elements at discrete stages of assembly/stressing. The intention of this work is to provide proof that element forces remain within their capacity, and feedback on local angular geometries of elements at key nodes. It also provides the contractor with evidence of likely forces and displacements that will have to be applied to the membrane at panel boundaries, for instance, in connecting them to the ladder trusses and their ridge cables.

Here is the common ground of the engineering effort by the designer and the contractor. We both follow similar thought processes and have developed similar "intellectual tools". These processes are informed by how things can be made and what is achievable, as well as by our understanding of the limits of our "tools" i.e. how well they model the physical phenomena we are dealing with.

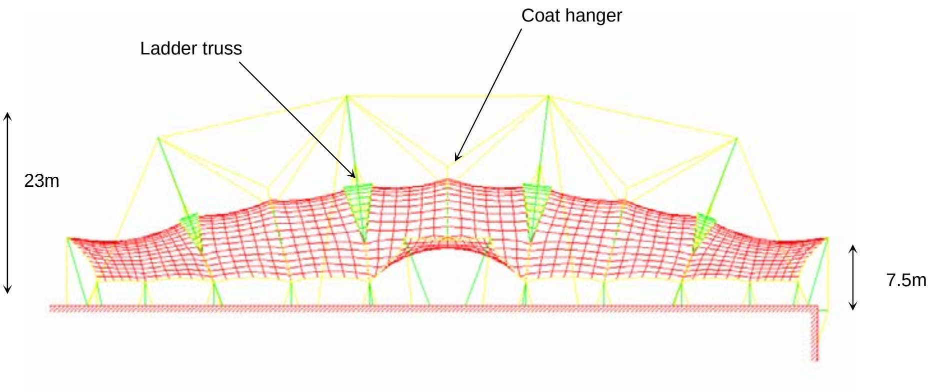

Figure 10 Dynamic Earth Centre long elevation

On this project the contractor is responsible for building the structure to a specified geometry and stressed state. The engineer is responsible for the design of the completed structure. The bid documents for this project reflected such a split of responsibilities and also indicated a sequence of "design development" activities that both parties would engage in post contract. Essentially during DD the principles of a credible installation and stressing method had to be established and fleshed-out.

DD was conducted in open dialogue between contractor, engineer, architect and construction manager.

Several major issues (which in themselves needed resolution) fed into this dialogue.

Brian Forster
Ove Arup & Partners
13 Fitzroy St. London W1P 6BQ 44 (0)171 465 3562 brian.forster@arup.com

- How many panels 5 or 8?
- Architectural appearance of site splices between membrane panels.
- Future panel replacement.
- Site limitations on access, phasing with other trades.
- The extent to which the primary mast and aerial tie system could be used to jack forces into the membrane.
- Access, safety of workers.
- The benefit and validity of the system offsets between membrane and the steel system lines as contained in the Arup model at contract stage.

The outcome of this process was a re-configuration of site splice detailing, agreed membrane to steel offsets and the execution of a preliminary erection analysis by the contractor to give confidence in the proposed erection method. This then enabled us to revise our structural analysis model, confirm member sizes for ordering and commence design and drawing of all steel to steel connections. We supplied our revised computer model to the contractor to assist him in his replication of the steel and membrane systems within his model.

This system of work is attractive and effective. Not surprisingly it requires discipline, the practice of foresight and the need to make as few changes as possible en route.

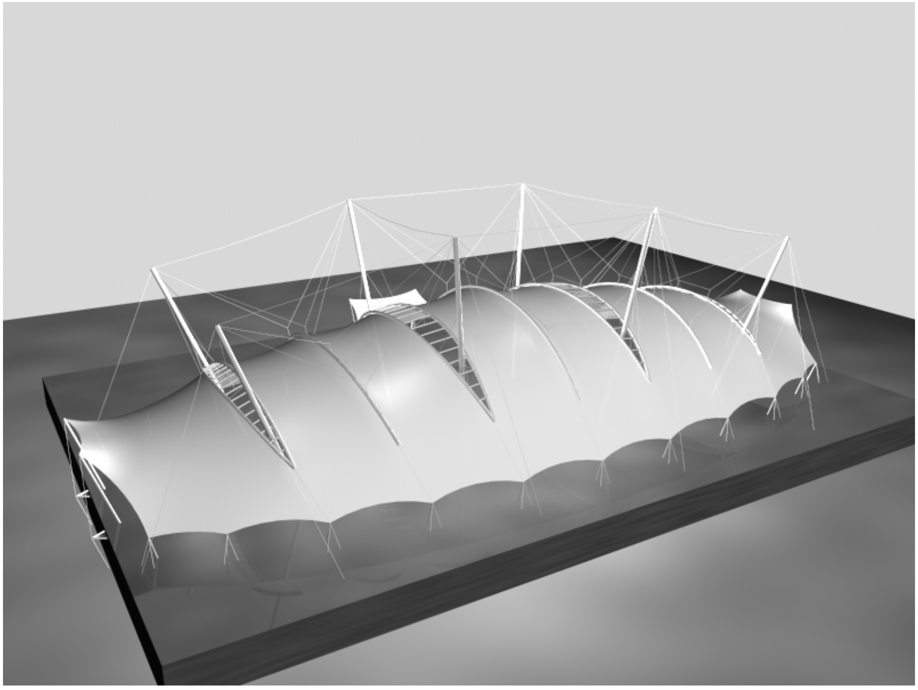

Figure 11 Dynamic Earth Centre computer visualisation