Theory and practice in the design of lightweight structures

The Design of the Millennium Dome

Ian Liddell

Introduction

In the year 2000, an event, the Millennium Experience is to be held on the Greenwich peninsular. After investigating ways of housing the exhibitions in conventional halls are large umbrella over the site was proposed by Gary Withers of Imagination Ltd and Mike Davies of Richard Rogers Partnership and was considered to be the preferred means of housing the exhibition and providing the facilities for the exhibits. The structure, which is now complete, covers an enclosed area of 80,000m2, twice the area of Wembley stadium, with a PTFE/glass fabric roof. The project has been the subject of continuous controversy and is likely to become an icon for the new millennium.

This is a paper about the development of the design of this structure and how it fits into the progression of engineering concepts for tension roofs. Such developments are driven by economic factors, environmental objectives, structural theories, methods of analysing and presenting conceptual models and also the available materials. These structures are interesting because they because they have no spare flesh on them. Their form is determined by the equilibrium shape of the elements in tension hence they require engineering understanding and skill to control and adjust.

The Site Conditions

The site is part of what used to be the largest gas works in Europe. It was originally a marsh and in common with many gasworks of the early part of this century was polluted by waste products from the coal gasification process being dumped on the site. It has now been cleaned up and a station for the Jubilee Line Extension is nearing completion. The Greenwich meridian runs through the west side of the site. In this context the construction of the Millennium Experience will speed up the regeneration of the site into an inhabited urban area.

Our initial aim was to design the structures for raft or pad foundations which would be founded at or just below the surface. A subsoil investigation was carried out and this revealed that the top 8-10m of fill and silty clay was softer than anticipated and the predicted settlements were of the order of 300mm. This amount of settlement could not be tolerated so the site would have to be piled with the piles bearing on the terrace gravels below the silt or into the London clay below that.

A further complication was the southbound carriage way of the Blackwall tunnel which passed under the proposed area for the building with a vent structure which would be within the building area. The additional ground loading over the tunnel was restricted to 20kN/m2 and any construction within 50m had to be approved by the HA. The piling solution was to use driven cast in place piles into the gravel for most of the site with continuous flight auger piles into the clay for the areas adjacent to the tunnel.

The Engineering concept for the roof

The concept is apparently very simple. Tensioned steel cables are arranged radially on the surface of the dome and held in space by hangar and tie down cables at 25m intervals. The surface is defined as a spherical cap. Between the cables, tensioned coated fabric is used as cladding. Both the tensioned cables and cladding carry the loads by deflection accompanied by increase in tension. This concept is simple but there are dangers associated with the deflections particularly ponding caused by snow or heavy rain. To ensure that the structure works satisfactorily it is necessary to understand the behavior of the materials and the structure as a whole and to get the details and the geometry right.

The original concept was for a roof that would have a limited life, just for the exhibition, and costs were to be kept to a minimum. The political position has now changed so that the structure is now intended to be "permanent".

Development of the Technology

Tension structures rely on the shape of the stressed surface for their performance under load. Forces are resisted by the tension and the curvature, the greater the curvature the less the tension to resist a given load. Marquee type tents rely on flat fabric stretched out by guy ropes. This deflects under load increasing both the tension and the curvature. Provided the surface is well sloped they drain without ponding. In the 60s Frei Otto developed a theory of using well curved surfaces with opposing curvature, minimal surfaces, with equal tensions under prestress. He worked with models to develop the structural forms and also to estimate the forces under load and to determine the fabric cutting patterns. He extended the technology from fabric to cable nets and used his formfinding methods to develop some structures that surprised the architectural world. We remember the West German pavilion at Montreal in 1968 and the roofs for the Munich Olympic games in 1972. Following this a government funded research group was established in Stuttgart investigating the design and technology of these structures.

In 1968 Ted Happold met Frei Otto at the prize giving for the Riyadh Conference centre competition and started a life long friendship which led to their collaboration on a number of remarkable projects. The most remarkable of these was probably the Mannheim Multihalle. This was a doubly curved compression structure constructed out of 50mm square timber and spanning 60m.

An other line of development in this field was air supported structures originally invented by FW Lanchester around 1910 but not properly developed until 1948 when improved materials became available and Walter Bird started building radomes for the US military. The research work to enable these radomes to be reliably built was carried out at the Cornell Aeronautical Laboratory in Buffalo, NY. Walter Bird's work led to the air inflated tennis halls and then to the American pavilion at Osaka and from there to stadiums with air supported roofs which had an area of up to 40,000 m2.

Buro Happold has been engaged in developing tensioned fabric and cable technology since the inception of the firm in 1976 and even in the case of some individuals before that. Interest in this particular field was initiated by Professor Sir Edmund (Ted) Happold FEng and was stimulated by his relationship with Frei Otto. Their first fabric structure was a temporary canopy for the opening of the Forties oil field in 1975. At this time fabric structures technology was in its infancy. The form of the surface and the patterns for making up the cloth were generated by measurement of physical models. The tent for the British Genius exhibition was designed in this way. A physical model was built and measurements taken from it and used for the construction. In fact there was no patterning, the fabric was flat cotton canvas which was stretched into the curved surface by distorting the angles of the weave.

However there were ideas around for developing computational methods for developing patterns. In 1977 Ted obtained some funding from the Wolfson Foundation for his department at Bath University to study air supported structures as a generic form of flexible structures. This group had a few post graduate students at the university but in addition Ted brought in a number of other interested people from a range of disciplines. The research studies included investigations into material properties and the internal environment as well as structural behaviour and the performance of actual structures in the field. The group held two symposia under the auspices of the Institution of Structural Engineers at which the results of the research were published.

At this time, in Buro Happold we set ourselves a target of developing a computer program which would handle both the formfinding of these structures and their load analysis. The program also can provide the fabric patterning and the other geometric information required for fabricating the components. We also picked up some commissions for fabric structures where we were able to apply this technology and ideas for structural forms and detailing. In each of these projects we would try out something new so that we were able gain an understanding of what worked and what didn't. The projects stimulated development of the software and the software allowed the projects to move forward. By 1980 we were able to process the patterns for this large canopy in Baltimore.

In 1980 we were appointed to carry out a feasibility study for a covered city in the arctic, actually in northern Alberta where the tar sands were mined and processed into oil. As part of this study we looked at the response of people living in an enclosed climate moderating space and concluded that in was necessary to have a transparent roof which let in the full spectrum of visible light. For this project we studied a 35 acre air supported roof which was to be clad with ETFE foil. This is a transparent fluoropolymer foil which has long life characteristics and reasonable strength and toughness.

Part of the study for 58^{o}N was the behaviour of air supported structures under snow loads. Some years later I was asked to advise the owners of the Minnesota Metrodome on problems they had had with their air supported stadium roof. These were mostly related to ponding during snow storms leading to collapse of the roof. Even though the roofs were designed for this eventuality, the collapses resulted in unacceptable damage and such roofs became unacceptable to the owners. The ponding problems were largely resolved in the design of the last stadium project with an air supported roof, that at Tokyo by using higher internal pressures. However the higher engineering standards required for this made these structures less competitive and stadium roofs are now constructed with cable structures as at Atlanta and St Petersburg. These structures all feature a compression ring and internal flying masts.

A part of this development process is testing out the public acceptance of the serviceability of large deflection structures, something that is difficult to predict. With the airhouse example above it was the owners who bought the technology because of the construction cost and they rejected it because of maintenance difficulties.

In Buro Happold we are still developing our computer software, now into the third generation of hardware. we also strive to maintain a group of engineers able to work with these structures. This means that we train engineers both in the UK and for our New York office where we are able to offer the same consultancy service. Another effect has been to train several other engineers in tension structure design who now have left us and set up their own firms.

Structural Form

The accepted form of surface stressed structures became the anticlastic doubly curved surface. Within this surface the down loads are taken by one set of cables or yarns in the fabric while the up loads from wind is taken by the other. Constructing the structural surface with this minimal surface shape stiffens it against loads but the change of direction of the forces made it less efficient.

The structural system for the Greenwich dome came from our observation that marquee tents did not conform to these types. They were flat fabric that, whether the load was upwards or downwards produced tensions in the fabric which are in the same direction. This system was developed for an arch supported roof over an arena. The arch supported straight cables which were stiff enough to stabilise the arch against buckling. Because the cables were straight the installation of the fabric could be simplified by sliding it into a groove in an aluminium extrusion. The arch supported roof was not built but two others were. These were the tennis halls at Eastleigh and the large audience tent for RSSB.

The Eastleigh structure was based on straight stringer cables suspended from ridge cables to make a two simple pitched roofs. The stringer cables were at 3m spacing and were infilled with inflated ETFE cushions. Environmentally the roof is a great success with the players who prefer to play there even when it is fine weather outside.

The RSSB tent is of particular significance since many of the structural elements are similar to the dome. It is a very wide marquee (120m x 180m) with a shallow slope which is designed to be easily installed by members of the community. The primary structure consists of cables running across the roof supported by masts at 16m spacing. The masts were kept as low as possible to make it easier to erect them by push-poling but this lead to a slope of 1 in 10. The roof fabric spanned 15m between the cable lines and was tensioned out at the ends of the structure. The fabric performed very well with out ponding or excessive deflections.

Design Development of the Dome structure

The original concept sketches done overnight in response to Gary and Mike's idea for a large covering, were for a cable structure 400m diameter with radial cables spanning about 25m between nodes and supported at each node. There were two rings of masts, a central ring of 12 and an outer ring of 24. The radial cable lines joined together towards the centre. The radial cable forces were to be taken by raking ground anchors in a typical marquee tent arrangement.

The concept quickly evolved; the diameter was reduced to 320m, the main masts were moved out and the outer ring of masts was dropped. To keep the tiedown cables clear of the planned internal structures the masts were supported on a pyramidal base 10m high and the outer ring of tiedown cables was eliminated by using external flying struts. This concept was analysed by computer and became the base design in Aug 96. At this point the architects RRP and ourselves were given a commission to prepare a scheme for the project for a planning submission to be made in Jan 97.

During this period several further developments were made. We realised that there was no advantage in combining the cable lines towards the centre and so we changed over to continuous radial lines which started from a central hub. The masts were moved further out and made higher to create a larger space in the centre and the external flying struts were eliminated. To improve the access to the dome at ground level the radial cables were collected by catenary cables to 24 anchorage points. It also became apparent that raking ground anchors would not be acceptable at all points and an arrangement of vertical anchors with a ring beam to take the horizontal component of the forces was adopted. Tender documentation for this scheme was completed and sent to contractors at the end of Dec 96

The straight cable structure is very efficient as far as strength is concerned, but it is necessary to ensure that ponding under snow or rain will not occur. The dome roof shape with tapering segments has an advantage in that respect in that as the span of the fabric panels increases their slope increases. However circumferential cables through the nodes were required to maintain their spacing. If these cables were in the surface of the fabric they would cause a dam at each circumferential line possibly initiating ponding, so an arrangement was required which would take these cables out of the surface. This was achieved by raising the circumferential cables above the surface with rigid members (wishbones) and connecting them to the nodes with criss-cross cables. Lower circumferential cables were also required to control the tiedown cables; these were also spaced off the surface but with out the criss-cross cables.

It was also necessary to control the deflection of the radial cables. Their length is very long, 150m from the perimeter to the centre. Because of this if one 25m span were loaded the remainder of the cable in the line would act as springs so the loaded span would not be as stiff as if it was fixed at each end. The only way to gain the necessary stiffness is to use a high pretension, in fact the planned pretension in each radial line is 400kN, about 2/3 of the peak tension. The last element in preventing ponding is the patterning and prestress in the fabric panels.

During the tender period some development of the design continued. We were concerned about the safety of the central node which had a single steel tension ring carrying a load of 7000N. If this ring were to fracture the whole roof would come apart and collapse. There was no way that an alternative load path could be included in the design. We decided to change the central node for a 30m diameter cable ring. This was constructed with 12 – 48mm dia. Cables. Because of the redundancy implicit in the 12 cables, failure of one of these cables would not compromise the overall safety of the roof. These changes were brought in to the contract package before the contract was finally placed.

Structural Detailing

With cable structures it is essential that the details respect the system lines and system points of the cables and their intersections, as well as the likely rotations of the cables at the connections. If the radial cables were continuous through the node points the flexing at those points would cause the cables to fail prematurely in fatigue. To avoid this flexing, the cables have to be terminated at each node and the connection details have to allow for rotation in both the vertical and horizontal planes. Barrel pins were used in clevis and plate type fittings to provide for these rotations.

The masts are constructed from 8 – 323mm diameter steel tubes braced with rings at 2.5m spacing. The cables are connected with radial plates at the top and bottom which are arranged to ensure that the cables theoretically meet at a single system point. The base of the mast is supported on the quadrapod with a rubber pot bearing to allow a small amount of rotation.

Design Verification

During the design development stages the structure was analysed using Tensyl, the bh software specifically developed for tension structures. This is able to handle large deflections of the structure under load. It can also calculate the form of the structure under specified tensions which represent the prestress condition.

The wind loads were initially derived from published data. Subsequently they were confirmed by wind tunnel testing carried out at the BMT tunnel in Teddington. generally the results from these tests were lower.

Ground snow loading was derived from statistical analysis of snow fall data from the nearest stations. The roof accumulation factors were taken from the snow loading code as well as other published references concerning snow drifting on large roofs.

The results of the Tensyl analyses gave peak loads on the components which were sized according to normal design rules. We were particularly concerned with the design of the 90m high masts which have to resist wind and icing loads as well as have sufficient resistance to buckling.

Resistance of the whole structure to accidental damage is provided by redundancy, i.e. the structure can tolerate the loss of an individual component without collapse. This principle also applies to the support pyramids which are designed to withstand the removal of a leg.

Selection of Cladding and the Internal Environment

The roof is to provide a controlled environment for the exhibition and for what other uses it may be put. Apart from the need for a blackout or light controlled environment for the central show space and for some exhibitions the human response preference is for a bright translucent roof with a light spectrum as close as possible to daylight. Coated fabrics tend to change the spectrum towards a brownish hue rather like tungsten lighting. This of course affects the perception of colours within the dome and according to our researches for the 58^{o} N project can affect the physical performance of people within the dome. Our objective was to have a total light transmission above 10% with the colour spectrum as close as possible to daylight.

It is difficult to have a translucent fabric roof with insulation but with out any insulation condensation will occur on the underside which, in certain conditions, will fall as rain. This situation would be totally unacceptable in a building that will have a lot of electrical displays. To reduce this risk a lining can be installed under the main fabric. There has been a considerable amount of experience with fabric roofs with linings where condensation has not been a problem. Checks were run on the risk of condensation as part of the environmental modelling and they demonstrated that with two membranes the risk of condensation on the underside was very low. The cladding was planned as two layers with the outer layer resisting the external loads and the inner layer sealed to it around the edges. The intention was to prevent dust entering the airspace during construction work inside the dome and to reduce the risk of water vapour migrating through the lining and condensing on the outer membrane.

The available fabrics for cladding the dome are PTFE coated glass fibre or PVC coated polyester fibre. The material must have properties of durability and flame resistance. These are provided by PTFE/glass without the need for any additives. The glass fibres are not affected by UV light but they are damaged by water. The function of the PTFE coating is to protect the fibres from water and abrasion, the PTFE itself is completely inert and not affected by the weather.

With PVC/polyester the fibres are damaged by UV light and they burn so the function of the coating is to protect the fibres from UV light as well as providing the flame proofing. The PVC itself is light stable and does not burn well but it requires a number of other compounds such as pigments, UV stabilisers, plasticisers, fungicides and flame retardants to meet the functional requirements. Fungal growth within the yarns has recently been improved by the use of anti-wicking treatments. Surface dirt retention has been improved by the use of fluoropolymer surface lacquers which give it a durable sealed surface. After a investigating the products of the three best coaters in Europe an outer fabric was selected which gave 15% translucency and a lining lining fabric which gave 75%. The combination gave the highest translucency, about 12%, and a good colour rendering.

PVC has become the focus of a world-wide campaign being waged by Greenpeace. Because of the high profile of the Dome roof it became an opportunity for their publicity campaign. Their claims concerning the release and effects of dioxins and the effects of pthalates in the plasticisers were investigated carefully by the design team who could find little scientific support for them. The design team also examined the alternative materials suggested by Greenpeace only to find that none of them was suitable for the dome

The decision to use PVC coated polyester was taken in late April 1997 when the Dome was expected to have a short design life. However the new government made it clear in their review of the project that all options should be kept open regarding the long term use of the Dome. This completely changed the basis on which the fabric was chosen and a subsequent review concluded that PTFE coated glass fibre was a more appropriate material. It will have a far longer life and avoids the dirt retention and discolouration problems of PVC so it will stay looking clean.

Sheerfill 2 and 5 were selected for the outer fabric. The liner material is Fabrasorb 2a. This material is lightly coated and has small pin holes claimed by Chemfab to improve the sound absorption. The holes also increase the dust collection and results in the fabric becoming dirty. We asked for the coating to be increased so that the material was not porous but this resulted in a browner colour and less light transmission. In the short time available we were not able to get Chemfab to develop a better product with say FEP to seal the surface. At this time construction is continuing beneath the roof and it is visibly getting dirty from dust and diesel smoke . The change to PTFE/glass did not affect the steel and cable structure but the fabric connection details were changed. The material will give a lower translucency and poorer colour rendering than the selected PVC options but it will look better externally and will continue to do so.

Environmental Modelling

Within the dome there were considered to be three different types of space; circulation areas especially the entrance corridors and the street around the central performance arena, The arena itself and enclosed exhibition buildings. Both of the last two are to be supplied with cooled air provided by local air handling plant. The circulation areas rely on fresh air being supplied at ground level and escaping at roof level to maintain reasonable temperatures. The external air comes in naturally through vents and doors in the external walls. To ensure that fresh air reaches the circular street which is 60m from the walls there will be air handling fans situated in the six perimeter plant rooms. To remove the air through the roof there are extract fans situated in each mast and 500m2 of openable roof lights in the centre of the roof as well as additional fans which would be used when it was raining

The comfort conditions within the dome were modelled by two methods, thermal analysis on a two dimensional section and computational fluid dynamics analysis (CFD) on a three dimensional model. In the CFD analysis the air flows as well as the heat transfer flows are modelled. The client was very concerned that the visitors would not be too hot both in winter when they would be wearing outdoor clothing and in summer. The results were presented as pictorial diagrams related to the relative warmth index.

.

Construction

The project is being procured through a construction management route. In this a number of separate contracts or "trade packages" are let. These contracts are between the client and the package contractors. They are managed by the "Construction Manager" (CM). There will be about 50 packages in the construction of the shell and core of the dome so it is a very complex operation.

Steel and Cables

The roof steelwork and cables were contracted to Watsons Steel and the PTFE fabric to Birdair. The cable work was subcontracted by Watsons to Bridons of Doncaster..

A critical part of this stage was planning the erection since the provisions for this would affect the details. Watsons preferred method was to assemble the cable net on the ground and then hoist it via the hangar cables to the mast tops. This required modifications to the mast tops to accept the cable winches as well as to the details at the connection of the wishbones to the cable nodes.

The lifting of the masts was been planned by Watsons with great care. This involved selecting a suitable 900 t crane and devising lifting positions which would not overstress the masts. Each mast was lifted and guyed with the two permanent backstays and two temporary forestays. There was also an intermediate position while the crane was released when only one forestay could be used and a short term guy was added from the centre of the mast to the adjacent base. While the mast was guyed with the temporary forestays the central ring was lifted by the permanent forestays.

Following the lifting of the ring, the guy system had to be moved to inside the ring so that the rest of the cable net can be assembled and lifted to its place. The stability of the mast with the two guy positions and the crane derigging position was checked using Tensyl. This took into account the sag and stretch of the cables and therefore predicted the true stability. During derigging of the crane and the operations of changing the guy positions the tensions in the guys had to be carefully controlled to maintain the stability of the mast.

Fabric

The contractor who had made the best offer for the PTFE/glass material was Birdair from Buffalo NY. They have been producing structures in PTFE for over 20 years including some 12 covered stadiums of approximately half the area of the dome.

The fabric patterning and attachment details will had to be modified to accommodate this alternative material and since time had been lost in the programme this had to be done in an very tight time scale. Because of the arrangement of the panels and the fact that the cloths were to be fitted in to dead lengths the patterns had to be extremely accurate. The fabric patterns were developed by Buro Happold using a cable net to represent the warp and fill lines of the cloth. This was necessary since the panels of the outer fabric ran radially on the roof and with 25m long cloths it was necessary to model the curvature of the fabric with angle changing of the weave. These base geometry patterns were converted into cutting patterns who also included the stretch compensations.

Internal Planning

The concept of the dome was to provide a covered area to house the exhibition with services including electric power, chilled water and water and drains. These services are provided to the exhibition areas via six service cores uniformly distributed around the perimeter. The cores would contain the primary services and would also be the location for the main toilets and restaurants.

Services distribution to the exhibition areas are via shallow trenches in the ground running radially and circumferentially. The construction of these and the ground finish are complicated by the requirement to have a gas impermeable membrane below the surface. To allow for secondary cable routes to minor exhibits it was decided to adopt a paving slab system wherever possible. These would be bedded on sand above the membrane so that they could be lifted and cables run beneath where required.

The project is running on time and within the budget

Credits

Client, The New Millennium Experience Co Ltd, Jennie Page, David Trench, Peter English, Andy Smith

Architects, Richard Rogers Architects Ltd, Lord Rogers, Mike Davies, Andrew Morris

Engineers, Buro Happold, Roger Webster, Tony Mclaughlin, Glyn Trippick, Paul Westbury

Construction Managers, McAlpine/Laing Joint Venture, Bernard Ainsworth, Colin Holdsworth

.

Roof steel and cable structure, Watsons, Joe Lock, Peter Miller

Roof Fabric, Birdair