THE DESIGN AND CONSTRUCTION OF THE MILLENNIUM DOME

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Synopsis

The idea of covering the whole site for the millennium exhibition to provide a protected environment followed the first scheme for housing it in a number of large buildings. This paper describes the engineering design and construction of the roof now known as the Millennium Dome. The design started with the engineering decisions that led to the fabric and cable structure. This concept was then developed into the final form of a spherical dome supported by 12 masts and the cables were arranged to eliminate dams in the surface that could possibly initiate ponding. The construction details were developed to accept the cable movements and to assist with the assembly process and special equipment was planned for lifting the net. The selection of PTFE coated glassfibre cloth is described along with the method of developing the cutting patterns and the attachment details.

INTRODUCTION

In the year 2000, an event, the Millennium Experience is being held on the Greenwich, UK, peninsular. After investigating ways of housing the exhibitions in conventional halls a large umbrella over the site was proposed by Gary Withers of Imagination Ltd and Mike Davies of Richard Rogers Partnership (RRP). This was enthusiastically adopted by the client as 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 but has already become the icon for the new millennium.

This is a paper about the development of the design and construction of this unique structure.

RÉSUMÉ

En l'an 2000, un événement, le Millenium Experience a lieu sur la péninsule de Greenwich au Royaume-Uni. Après avoir étudié les nombreuses façons d'organiser les expositions dans des halls conventionnels, Gary Withers d'Imagination Ltd et Mike Davies de Richard Rogers Partnership (RRP) ont suggéré un toit en forme d'ombrelle. Cette proposition fut adoptée avec enthousiasme par le client, et cette solution fut choisie pour accueillir l'exposition et offrir toutes les installations nécessaires. La structure, qui est à présent achevée, recouvre une surface de 80 000m^2, ce qui représente deux fois la surface du stade de Wembley, et elle supporte un toit en PTFE/tissu de fibre de verre. Le projet a fait l'objet de débats continus, mais il est devenu le symbole du nouveau millénaire.

Ce document décrit le développement de la conception et de la construction de cette structure unique en son genre.

ZUSAMMENFASSUNG

Im Jahr 2000, ein Ereignis, wird die Millenium Erfahrung in Greenwich, UK gehalten. Nach Erforschung verschiedener Wege für die Unterbringung der Ausstellungen in konventionellen Korridoren, wurde ein großer Schirm über der Stelle durch Gary Withers von Imagination Ltd und Mike Davies von Richard Rogers Partnerschaft (RRP) vorgeschlagen. Dieser wurde begeistert von dem Klienten angenommen, als die bevorzugte Weise der Unterbringung der Ausstellung und der Austellungsstücke. Die Struktur, die jetzt vollständig ist, bedeckt ein eingeschlossenes Gebiet von 80,000mê, zweimal die Fläche des Wembley Stadions, mit einem PTFE/ Glas-Stoff-Dach. Das Projekt ist das Thema von ununterbrochener Kontroverse gewesen, aber ist schon die Ikone für das neue Jahrtausend geworden.

INTRODUZIONE

Quest'anno, nella penisola di Greenwich, Regno Unito, si sta svolgendo l'evento "The Millennium Experience" (L'Esperienza del Millennio). Dopo avere investigato la possibilita d'alloggiare le esposizioni in varie hall convenzionali, Gary Wither della Imagination Ltd e Mike Davies della Richard Rogers Partnership (RRP) proposero d'installare un ombrellone gigante sul sito. Questa soluzione venne adottata con entusiasmo dal cliente come la soluzione favorita per ospitare l'esposizione e fornire gli impianti per gli oggetti esposti. Ora completata, la struttura ricopre un'area racchiusa di 80.000 m, il doppio rispetto a quella dello stadio di Wembley, ed e dotata di una copertura di PTFE/tessuto di fibra di vetro. Pur suscitando una polemica continua, il progetto e devenuto l'icona del nuovo millennio.

Questa relazione tratta lo sviluppo del progetto e la costruzione di questa singolare struttura.

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 was poorly compacted waste lime from the gasworks above silty clay. This was found to be softer than anticipated with the predicted settlements of the order of 300mm. This amount of settlement could not be tolerated so the site had to be piled with driven cast insitu 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 Highways Agency. 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 structural concept is apparently very simple. Tensioned steel cables are arranged radially on the surface of the dome and held in space at the nodes 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 some increase in tension. This concept is simple but there are dangers associated with the resulting deflections particularly ponding caused by snow or heavy rain. To ensure that the structure works satisfactorily it is necessary to understand the behaviour 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 changed with the election of a new government and 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 required 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 pre-stress. 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.

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.

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 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 tie-down cables clear of the planned internal structures the masts were supported on a pyramidal base 10m high. 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. One of the first things that we did was to prepare a programme for the design and construction of the roof structure to ensure that it could be completed by July 98. This would allow 12 months to complete the interior and 6 months for exhibition fit out, commissioning and rehearsals. To meet this programme we realised that it was necessary to send out the tender documents for the steel and cable work by Jan 97.

During this period several further developments were made. The masts were moved further out and made higher to create a larger space in the centre. To improve visual appearance and the access to the dome at ground level the radial cables were collected at the perimeter by catenary cables to 24 anchorage points at ground level. 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 after 3 months of concentrated work.

The straight cable structure is very efficient as far as strength is concerned, but it relies on deflections as a part of its load carrying behaviour. Consequently 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 could 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 pre-stress 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 7000kN. 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.

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 pre-stress condition.

The wind loads were initially derived from published data. Subsequently they were confirmed by wind tunnel testing carried out at the British Marine Technology tunnel in Teddington. Generally the results from the tunnel 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.

The overall diameter of the masts was limited by transportation requirements and a great deal of computer calculation went into verifying their load capacity. The limiting load was calculated using LUSAS in a non linear mode. Since the masts are leaning deflections under self weight and icing have to be taken into account as well as initial out of straightness. Wind loading is also significant but this does not occur with the peak down loads from snow and icing.

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. 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 be full 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. PTFE/glass structures have been in service now for more than 25 years and only two have been replaced. The fabric is regarded as a very long life material.

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 fabric which gave 75%. The combination gave the highest translucency, about 12%, and a good colour rendering.

The roof was originally designed in PVC coated polyester when the Dome was expected to have a short design life and the aim was to minimise costs. However in June 1997 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 the manufacturer to improve the sound absorption but can cause an increase in dirt and dust retention. 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 for a long time.

The fabric patterning and attachment details 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 within the cable net and the fact that the cloths were to be fitted in to dead lengths the patterns had to be extremely accurate.. Since the warp direction of the panels of the outer fabric ran radially on the roof with 25m long cloths it was necessary to model the curvature of the fabric with angle changing of the weave. Buro Happold considered that this had to be done using an equal mesh net to represent the warp and fill lines of the cloth, a much more time consuming method than the standard method of representation using triangular elements. These basic geometry patterns were converted by the Fabric contractor into cutting patterns. They also built in the stretch compensations which were agreed after biaxial tests on the actual production cloth and added in all the edge details.

Contractual Arrangements

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). The CM programmes the interface between the individual package contractors and is responsible for the overall cost control of the whole project. All instructions to the package contractors are issued through the CM. The engineer retains responsibility for monitoring the technical quality on site while the CM controls the packages contractually and commercially. This arrangement allows for elements which can be constructed later to be tendered separately when their design has been completed and also allows for package contractors to be appointed on a "design and construct" basis where they can maximise their expertise in a particular field. There will be about 70 packages in the construction of the shell and core of the dome so it is a very complex operation.

The construction Manager, McAlpine Laing Joint Venture was appointed in February 97. After a four month tender and assessment period Watson Steel were appointed in March 1997 with a 52-week programme to detail and fabricate the structure steelwork, procure cables and construct the Dome.

Engineering

Watsons spent the initial few weeks developing the construction scheme and agreeing principles of connection design. Many important engineering decisions were made during the development of the construction scheme and a number of cost saving measures were also agreed. These included:

a) Reducing the overall numbers of cables by running the cables through the connections and clamping in lieu of stopping off and starting the cable with fork end connectors.

b) The overall cross-sectional area of the masts was reduced slightly to allow the sections to be moved by conventional road trailers without excessive notification periods. In order to achieve this some of the individual tubes were increased in thickness.

c) The original detail of the mast head involved solid discs at various levels, which prevented access through the centre of the mast. These were redesigned as annuli to allow access for temporary pulling cables and erectors.

d) Platforms and ladders were introduced which benefited the construction scheme as well as being a permanent requirement.

e) The original 'sandpot' detail of the base of the masts was replaced with a flexible rubber pot bearing.

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 complete project including the cables was fully detailed within the Watson drawing office at Bolton based on the construction drawings and geometry issued by Buro Happold. One of the most complicated 3D problems was the detailing of the huge mastheads. There are 23 separate cables, which have to connect into the masthead with a common intersection point. During detailing it was found necessary to extend many of the connector plates outwards to allow the individual cable ends to connect without clashing with each other.

The masts themselves were relatively simple to detail with all the joints, including the site joints, being fully welded. All 12 masts are also identical and interchangeable. At the bottom of each mast is a rubber pot bearing with a single locating bolt. The bearing allows slight rotation of the mast at the connection point with the pyramid.

The pyramids themselves are constructed from four tubular legs, site welded to a common hub. The ends of the tubes were detailed and profiled before delivery to site to ensure the best possible “fit-up” at the tube/hub joint.

The 3D geometric model of the Dome, developed by Buro Happold, produced the system point-system point length of the cables under working stress. The weldments at the cable intersection points, had to be fully developed before the cable lengths could be determined.

The cables were ordered initially to an approximate length to allow procurement to commence. The exact length was then firmed up prior to final measuring and cutting.

The pin-pin lengths of each cable were calculated by subtracting the end connection lengths from the system point - system point dimensions. The pin-pin lengths and the working loads were then provided to the Cable Manufacturer, who subtracted a standard allowance at each end to derive the "cutting length".

Because the "cutting lengths" were specified at the working load, each of the cables was load cycled on a 750m long track at their plant to eliminate the construction stretch. They were then marked at the specified load before being cut.

Fabrication of Masts

Each of the 12 masts is 90 metres long and weighs approximately 95 tonnes. The mast is octagonal in cross section with all the longitudinal members being 323mm diameter circular hollow sections. The lateral members are RHS section 300 x 200mm. For aesthetic reasons and also economy all the joints are fully welded. The 95 metre long masts had to be split down into 6-16m long sections for delivery to site. It was possible to obtain the tubes from the rolling mills in 16m lengths so it was not necessary to join tubes in the factory.

Fabrication of the mast sections had to be carried out to very fine tolerances to ensure that the mast sections would fit together on site. In order to achieve this, sets of matching templates were produced which maintained the cross sectional dimensions between the tubes to a tolerance less than ± 1mm.

This attention to detail was essential considering that some of the sections were fabricated in Bolton and other matching sections in Bristol. The true test came on site in July 1997 when site assembly commenced. All the mast sections slotted into each other perfectly. The mast sections were also interchangeable which demonstrated how well the tolerances had been achieved.

In terms of fabrication the most complicated part of the project were the 12 masthead assemblies where the hanging cables connected. These assemblies weighed 12 tonnes each and were fabricated from plates 20-50mm thick connected to a thick central tube.

Assembly on Site

Assembly of the masts and pyramids commenced in July '97. Concrete blocks equipped with adjustable supports were cast insitu to support the masts during assembly. The six sections were fitted together in the jig using a tapered backing strip at each joint. The masts were set up with 50mm of camber to counteract the sag under self weight. The care and attention put into the fabrication paid dividends and the sections fitted together perfectly. The overall length of the mast could be adjusted slightly by the tolerance of the welding gap. At the assembly stage the length was set 9mm long in anticipation of the weld shrinkage. In the event the allowance proved to be correct as the overall shrinkage was recorded between 6 and 10 mm.

All the site joints were full strength butt welds which were then ground smooth. The welding process used was "inner shield" which is a semi-automatic flux cored wire process. Purpose made covers were manufactured to protect the joints from rain during welding although the process used is reasonably robust and can withstand moderate wind without detriment. The 480 full strength butt welds were completed in a seven week period without a single repair being required.

Following welding, testing and painting the complete masts were lifted from the assembly jig and carried out into the Dome Arena. In some instances a distance of 500 metres. This was achieved with a large crawler crane of 210 tonnes nominal capacity.

The 12 pyramids, which were assembled in parallel with the masts were also carried from the assembly yard and installed first onto the inclined concrete bases. The bases had been predrilled using a full size template measuring 10 m x 8 m. The locating bolts were resin anchors which were fixed after the pyramids had been placed.

Erection

Prior to erection the masts were also fitting out with various temporary works, permanent ladders and platforms 15m below the top. The temporary works included a small cable hoist to take personnel to the top platform.

On 15th October 1997, a large strut-jib crane with super-lift was assembled on site to lift the first masts in front of a large assembled crowd of V.I.P's and the world's press. This operation was completed successfully and during the following 16 days the remaining 11 masts were successfully erected.

In their final position the masts are restrained by the forestay cables attached to the central hub and the back stay cables. At the initial erection stage however, the permanent forestays could not be used and two temporary cables were required to supplement the 2 back stay cables to stabilise the mast. To restrict movement of the mast head, the cables had to be post tensioned to 300 kN load. This required the sag and slack in the system to be taken up which meant jacking a length of about 1500 mm in increments of 250mm. The masts had to be held by the large crane during this process which took between 5-9 hours.

The masts in their permanent stage are primarily under compression with bending stresses from wind and dead loads. During erection however the condition is very different. It was originally planned to lift the mast from a single point which would have allowed the mast to rotate easily from horizontal to near vertical. Design checks however, showed that local failure of the tube/tube joints would occur and it was necessary to lift the mast at four positions. This then gave some practical difficulties in rearing the mast since the lifting wires were required to change length. This was resolved by designing a special lifting beam with two pulley blocks to allow the two lifting wires to run through. Refer to figure 6. This arrangement also guaranteed that the load was spread equally between the four pick-up points.

To assist in the rearing operation and to prevent the bottom of the mast dragging on the ground a second crane was used to tail the bottom of the mast. Temporary tapered "spears" were attached to the bottom of the mast to help locate the single 52mm diameter bolt into the 3mm clearance hole during erection. The masts slope at 17º to the vertical and an inclinometer was also attached to the mast during erection to ensure the correct angle was obtained.

Installation of the Cable Net

The cable net consists of individual cables connected together using fabricated and galvanised brackets at each node. In developing the cable installation scheme, we applied the same principles as any high level erection project, which is to minimise the risk by carrying out as much work as possible on the ground and lifting the assembly in as large sections as is practical.

Many different schemes were considered and costed until eventually the present scheme was developed. The principles of which were:-

a) Assemble concentric rings of cables on the ground.

b) Install the individual radial cables between the rings at ground level.

c) Using temporary extension cables attached to the permanent hangers the rings were pulled up using 3 separate cable jacks on each of the 12 masts.

d) The separate infil radial cables between the circumferential rings were then installed

e) Finally the cable net was post tensioned.

The spiral stand cables are particularly susceptible to kinking if not handled carefully. All cables were either delivered as a loose coil (if less than 30 metres long) or on a drum if longer than 30 meters. Methods of handling and laying out were developed to minimise the risk of damage to the cables.

The central 30 metre diameter ring consists of 12 separate 48mm diameter cables. These pass through 72 separate brackets where the 72 pairs of radial cables terminate. In order to accurately locate the 48mm diameter cables and the brackets a 30 metre diameter template was constructed to fire tolerances. Figure 1 shows the assembled ring on the steel template. The complete central hub assembly was then hoisted from the mast heads using the 12 principle forestay cables each with a temporary pulling cable attached as shown in figure 7.

At this stage 12 temporary tie down cables, attached to ground anchors were fixed to the 30 metre diameter hub. These provided the necessary restraint to the top of the masts via the forestay cables and allowed the initial temporary erection cables to be removed. (This was necessary because they would have prevented the lifting of the next cable ring which would have to pass through the temporary cables).

The level and location of the central hub was adjusted by stressing the 12 temporary tie down cables. At this stage the central hub and the mast heads were positioned to within 30mm of the true position.

The outer cable nets meanwhile were being assembled on the ground. The cable net node positions were first marked out on the hardcore using paint. The connecting brackets were then positioned at each node point. The cables were laid out between the nodes using a specially adopted turntable on a truck and a fork truck. The sequence was to ensure that access to each workfront was maintained without the need to drive over previously laid cables.

The assembled cable rings of up to 360 metres circumference were lifted by pulling up all the hangers simultaneously using 36 separate pull jacks located at the top of the masts. Each mast was fitted out with a self contained diesel power pack, a control panel and 3 jacks each with a 300 metre long 16mm diameter pulling cable. The arrangement of the equipment is indicated in figure 8. All the temporary equipment was designed specifically for this project and a full working trial was carried out in the fabrication yard in Bolton in the Autumn of 1997 which resulted in a number of improvements being made.

The lifting of the cable nets was achieved using 12 operators each controlling three jacks. All jacks were given a unique code number and the foreman in charge controlled the lift by radio via the operators. Since the net was flexible there was little risk of load transfer between the jacks and it was only necessary to control the level of the lifting points to a margin of approx. ± 1 metre. This was achieved visually.

The nets were raised at a rate of about 10 metres per hour once the initial slack had been taken up. Once the net was at its full height and the cable ends within range of the mast head, the difficult task of attaching the cable ends to the huge gusset plates could begin. This operation, at 100 metres above ground level, was carried out by 24 abseilers working in pairs. They climbed through the top of the mast and abseiled down the outside to the connection points. A third man controlled the pull jacks and received instructions from the abseilers. In this way the fork ends were eased over the gusset plate connectors and the pins installed.

This operation was carried out during the winter months of 97-98, often at temperatures well below freezing, until eventually by mid February 1998 the last of the 276 high level pins was installed.

The temporary clamps, pulling cables and pull jacks could now all be removed by the abseilers and lowered to the ground. With the exception of the final clean down and touch-up the work at the mast heads was now complete.

Fabric Installation

The contractor who had made the best offer for the PTFE/glass material was Birdair from Buffalo in the USA. 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 attachment detail proposed by Buro Happold was a double luff groove extrusion fitted onto the radial cable pairs to accept a roped edge on the fabric. Birdair proposed to use a 12mm edge cable in the fabric which would hook into special clamps fixed to the cables. The clamps were developed into a two part extrusion cut into 50mm lengths, fixed to the cable pairs at 500mm centres and retained by two 12mm bolts.

Birdair as well as being responsible for the supply and installation of the fabric were also responsible for other details such as gutters, hoppers and diverters built into the fabric panels. Each segment of the dome was divided in two, Circ 1-4 and circ 4-7. Consequently the roof comprises 144 separate panels of fabric. The panels were fabricated in Birdairs manufacturing facility in Buffalo from lengths of cloth 2m wide by heat welding the seams. Each panel comprised the inner layer of fabrasorb welded to the outer layer of sheerfil. An additional length of sheerfil fabric was welded to each side of the top surface of the outer layer to form a closure flap which would form the seal between adjacent panels. The panels were carefully folded packed in crates and shipped to the UK.

Installation started from the centre using a central scaffold tower which had been erected primarily for the installation of the central roof vents. A moving hanging platform was erected between circs 1 & 2 and 2 & 3. This was capable of being moved along the circumferential lines from segment to segment. Each panel was pulled out from a platform near circ 3. It had been folded in such away that 2/3 of it could be unfolded towards circ 1 followed by 1/3 towards circ 4. The panel was temporarily supported on a net of ropes and belts between the radial cables. Once it was fully opened out the edge cables were inserted in the edge cuffs of the panel and fixed at the ends. The fabric panel was stretched sideways and the edge cables were then hooked into the fabric clamps on the cable lines. The target pre-stress in the fabric was 4 kN/m so a variety of pulling devices were required to bring the edge rope into the hooks.

Once the circ 1-4 panels were fully installed work started on the circ 4-7 panels. Light aluminium gantries were hung from the cables for access. Where the fabric was already installed abseilers would work from it on one side. The folded panels were lifted into the air by mobile crane and unfolded onto the temporary net of ropes and fixed in a similar manner to the circ 1-4 panels. Once the panels were all attached the closure flaps were temporarily fastened with a standing seam made with a bag stitcher. The panels then had to be joined at circ 4 with luff groove extrusions and tensioned out to the boundary cable where it was fixed with clamps. All the panels were installed by the 19 June 1998, one year after piling started.

The tunnel vent area was effectively a separate project. A 50m diameter hole was required in the roof. After considering a number of way of leaving a hole in the fabric, Buro Happold decided that the best way was to infill the hole with a net of 8mm cables at 1m spacing which would replicate the fabric but allow the vent air to pass through. The cable net was attached to the fabric with clamp bars at the edges. The cable net and the surrounding fabric panels had to be patterned separately and all the dimensions worked out. The net arrived on site in rolls and was erected in the same way as the fabric using the same extruded hooks modified with a steel plate to which the cable terminations were attached.

Once all the panels had been installed the joints between adjacent panels were properly sealed against water penetration by heat sealing the closure flaps. This was done with a hot iron, heated to 380°C and an FEP interlayer. At the nodes the fabric was fixed to the flat surface of the steel node assembly with adhesive and finally sealed with PTFE fabric boots. At circ 1 additional PTFE fabric flashings were welded to the panels and fixed to the central ventilation assembly to provide the waterproof seal at the top. At the top of the perimeter masts the panels had been patterned around the cable net jacking positions forming an elliptical opening. This opening was sealed by covering with a stretched fabric cap on arched steel tubes. PTFE glass cloth was not suitable for this purpose and so acrylic coated glass cloth was chosen. This material retains dirt and dust more that the PTFE fabric and so discolours with time. The architect therefore chose to use a yellow colour for these caps – a colour similar to the paint on the steel masts.

Where the main masts penetrate the roof a stainless steel tubular ring was fixed around the mast spaced from it. The ring was designed to lift the fabric above the general plane of the roof to divert rainwater. The space between the mast and the ring was infilled with clear polycarbonate panels in aluminium frames – much like a traditional rooflight. Secondary gutters were installed beneath the rooflights. The casing to the ventilation extract fans installed inside the masts at these locations formed the barrier to rainwater penetration within the masts.

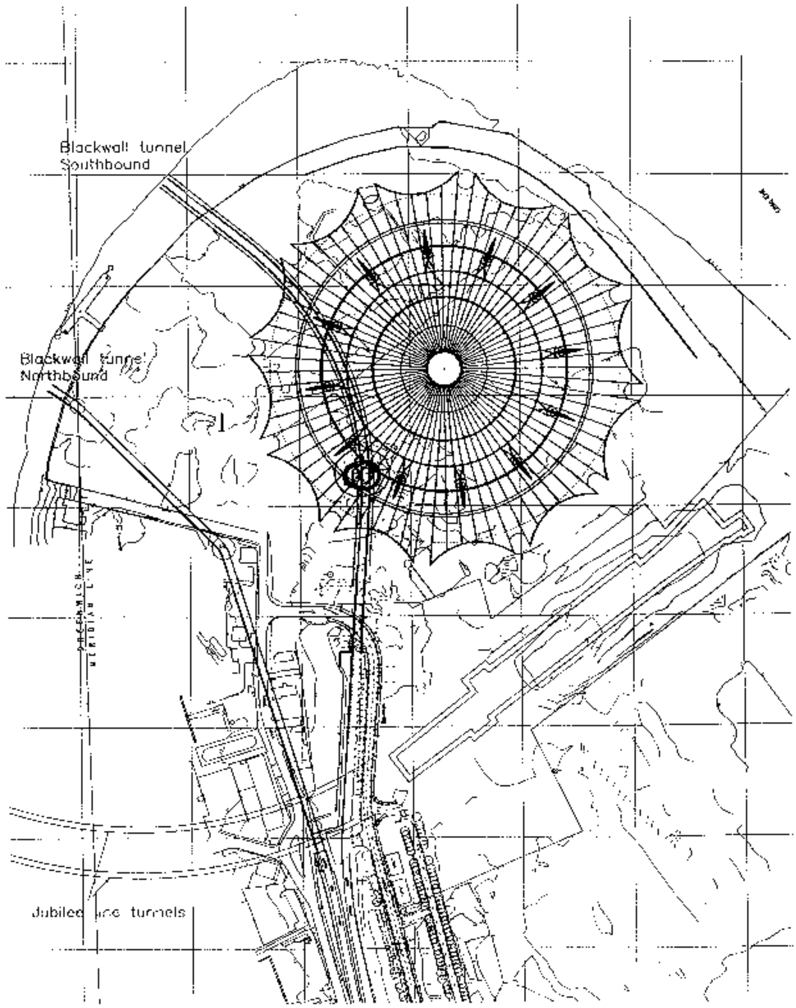
Rainwater run off from the roof is collected at the perimeter by an aluminium gutter which channels the water to the 24 hoppers located at the roof anchor points.

The fabric work was finally completed at the beginning of December 1998.

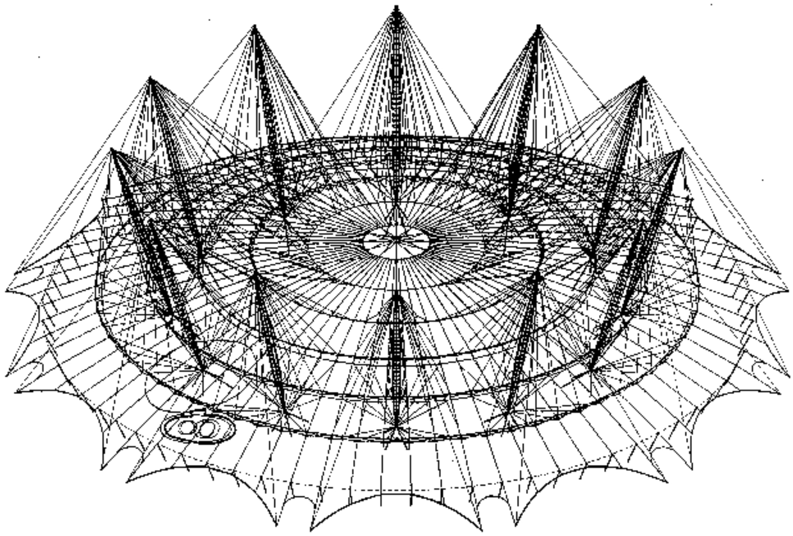
Acknowledgements

Client	The New Millennium Experience Co Ltd, Jennie Page, David Trench, Peter English, Dick Coffey
Architects	Richard Rogers Architects Ltd. Lord Rogers, Mike Davies, Andrew Morris
Engineers	Buro Happold. Ian Liddell, Roger Webster, Tony Mclaughlin, Paul Westbury

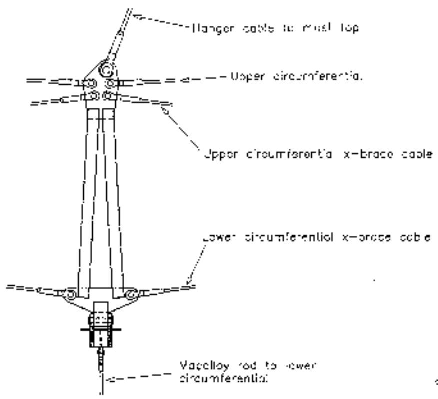
Site Plan


Blackwall tunnel
Southbound
Blackwall tunnel
Northbound
Jubilee line tunnels

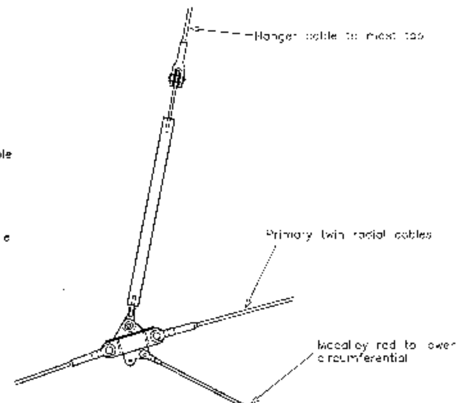
Isometric of Cable Net



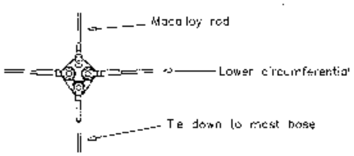
Detail of node on the radical cables



Wishbone elevation

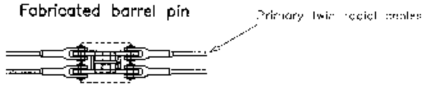


Wishbone section



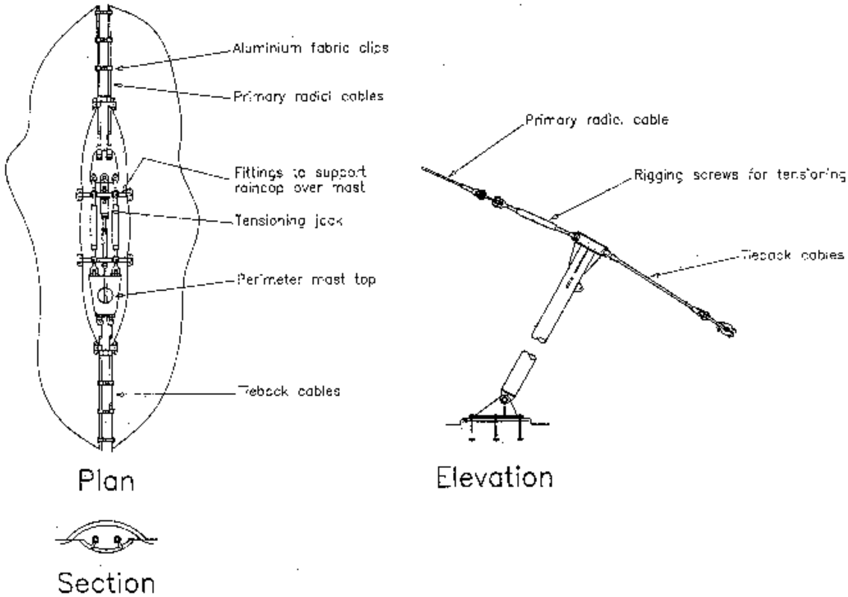
Lower circumferential connection node

Fabricated barrel pin

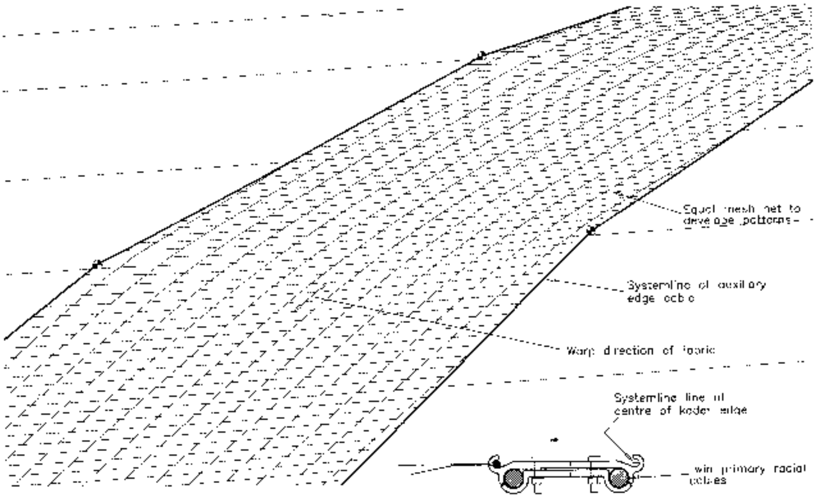


Wishbone node plan

Detail of radical cable connections at the perimeter masts

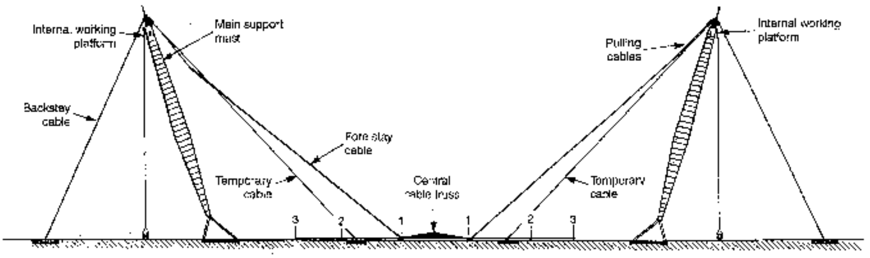


Fabric patterning model

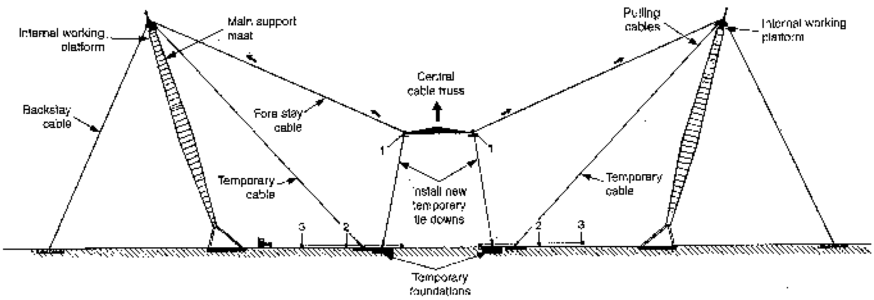


Section Through Standard Aluminium Connection Extrusion

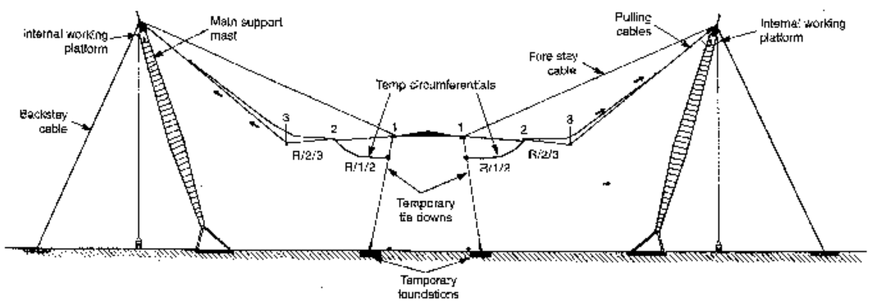
Arrangement of masts restrained by temporary forestays before lifting of the inner ring



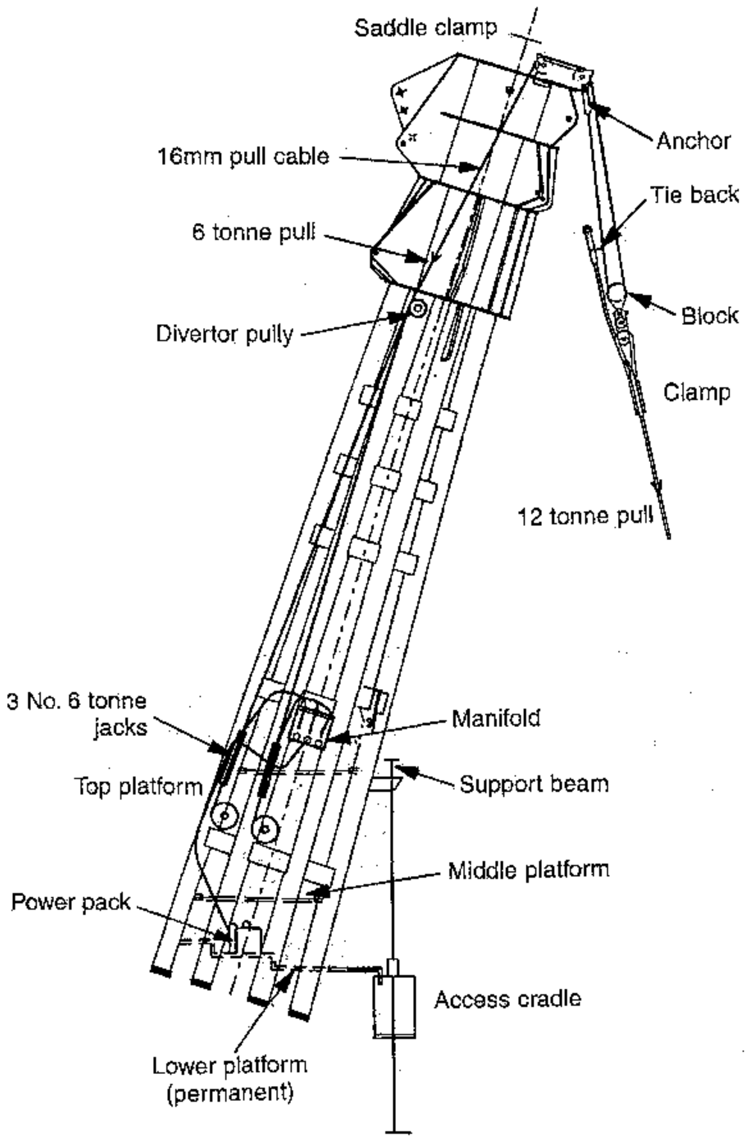
Arrangement with inner ring lifted and new tie-downs installed



Arrangement with temporary forestays removed and second ring lifted



Arrangement of lifting equipment in the masthead



EDP CENTRE OF THE ASSICURAZION GENERALI INSURANCE COMPANY AND THE CENTRO CONGRESSI FIRENZE

DR Arch Guido Spadolini Florence Italy

The EDP Centre, located in a modern complex in Mogliano Veneto, houses the Italian head office of the Assicurazioni Generali insurance company, which is responsible for Italian insurance market operations and employs some 5,700 persons.

The speaker, Guido Lorenzo Spadolini, will make a general presentation on the design and construction of his father's project.

The architect, Pierluigi Spadolini, adheres to an architectural philosophy aimed at blending environmental harmonies, paying special attention to the historical and environmental setting of a new scheme.

Spadolini's new building stands alone in the countryside with a distinctly clear-cut profile. The perpendicular block of the EDP centre forms the hub of the whole complex. Whilst it had to be constructed like a fortress, the architect wanted to retain an atmosphere, which would be conducive to a productive working atmosphere.

The speaker graduated as an architect from the University of Florence in 1975. In 1988 he founded the Studio Spadolini & Associati with his father and has commissioned many architectural projects.

The Centro Congressi is house in the 19th Century Villa Vittoria, originally built by the Strozzi Family from Mantua and renovated in 1931 when the Contini Bonacossi family bought it. The centre is host to meetings, exhibitions, festivals and other events seating from 10 to 1,000 people, including the XIth IWA and NRCA Congress.

For a virtual tour of the Centro Congressi visit their web site www.centrocongressi.it