Creative Engineering for Fast-track Design: The New Benfica Stadium Roof Structure

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When a world class stadium is designed to host the Euro 2004 international football championships, for a European football club steeped in history, it needs a dramatic and unique architecture to set it apart from other similar venues. Added to this, the need to cover 65,000 seats with uninterrupted views serves to drive forward the design of major structures to span the immense spaces below. The structure of the roof of the new Benfica Stadium has provided a striking but elegant and efficient response to these prerequisites.

In this paper the development of the roof scheme on a fast track design and construction programme is discussed. The design addressed the need to progress the construction of the stand structures below whilst final analyses of the structural steelwork were completed. Earthquake and temperature effects have been incorporated into the design and comprehensive analyses carried out to fully address second order effects and overall buckling failure mechanisms.

As well as the structural design principles, issues covered include the emotional considerations of designing such a structure as a replacement to an existing stadium much loved by its supporters, and the careful control of the cost of the structure within a limited budget.

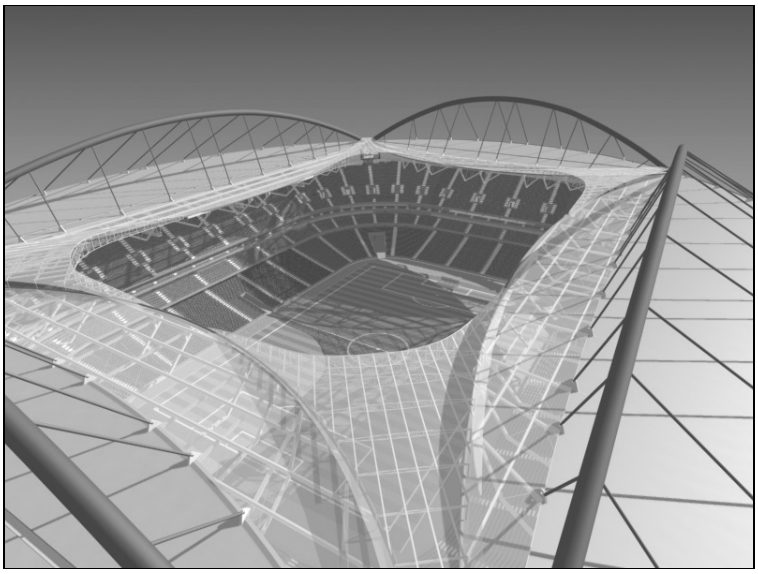

Figure 1: General view of proposed roof

INTRODUCTION

Since the award of the Euro 2004 football championships to Portugal, the nation’s stadiums striving to host the event have been transformed through new build and refurbishment works. It was important for Benfica Football club (Sport Lisboa E Benfica), as a major Portuguese club steeped in history and tradition, to play a major role in hosting the championships. To be in contention, the existing stadium, extended in the 1950’s, required a major re-think to meet modern day standards for international venues.

A variety of options, from renovate to relocate, were developed to enable the club to fully assess the options and develop a business plan from which financing could be sought.

Schemes to convert the existing stadium and install a new roof were found to be impractical, given the time frame and necessity to keep the existing stadium operable at club level right up to the time of the championships. The proposal eventually selected involves the construction of a new stadium on the land previously occupied by the practice pitch alongside the existing stadium. During the time of construction, the existing stadium will remain in operation. Adjacent to the new stadium a pavilion structure is to be constructed enclosing additional sports facilities for the Benfica basketball and roller hockey teams.

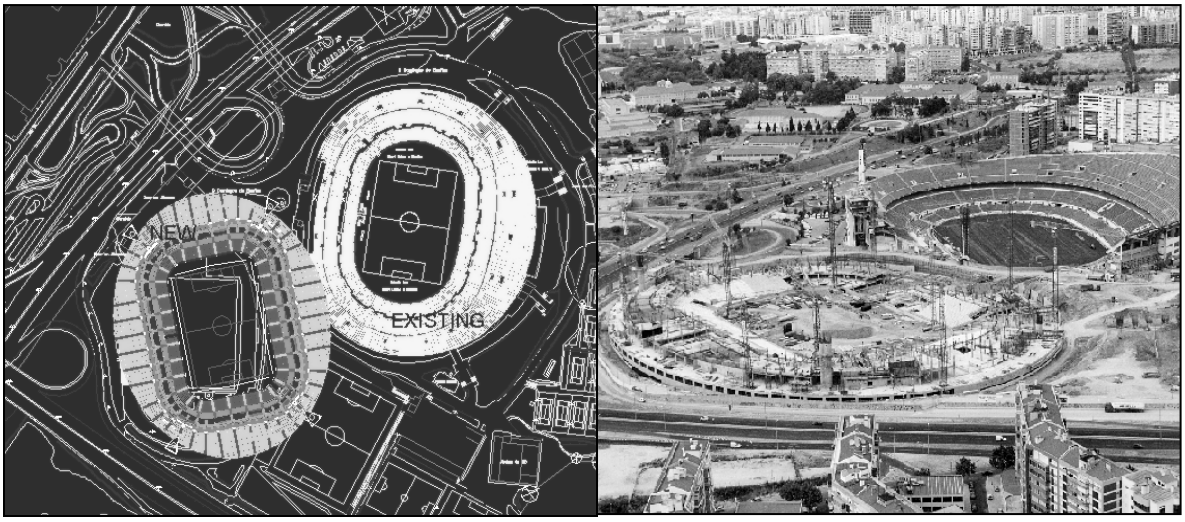

Figure 2: Plan of new and existing stadia. Aerial view of site

To many football supporters around the world their clubs stadium becomes a second home. Consider then the passion to be found around one of biggest and most famous clubs of Portugal - a football mad country, which produces no less than three daily newspapers focusing primarily on the sport. Benfica Football Club has a massive following in Portugal, Brazil and Africa (not to mention the many other supporters worldwide) and was also home to Portuguese football legend Eusabio. Coupled with this, there is an intense rivalry between Benfica and the other major club in the city, Sporting Lisbon. Hence the new stadium had to be a major landmark building fitting for such a proud and historic club.

A prominent roof structure became an important aspect of the design which, as requested by the Client, will maximise the visual impact of the building. The European footballing body UEFA requires that venues for major championships have a roof covering for the majority of the seats. An important consideration in its design was the fact that the existing stadium does not have a roof giving the seating bowl a dramatic sense of space, lightness and openness and from a practical side, promoting grass growth (figure 3). Hence the new stadium has to live up to the expectations and precedents set out by the Estadio da Luz (the Stadium of Light). However, the roof structure can be used as an opportunity to create a distinctive architecture and a symbol of the club which the supporter will consider part of the identity of the club.

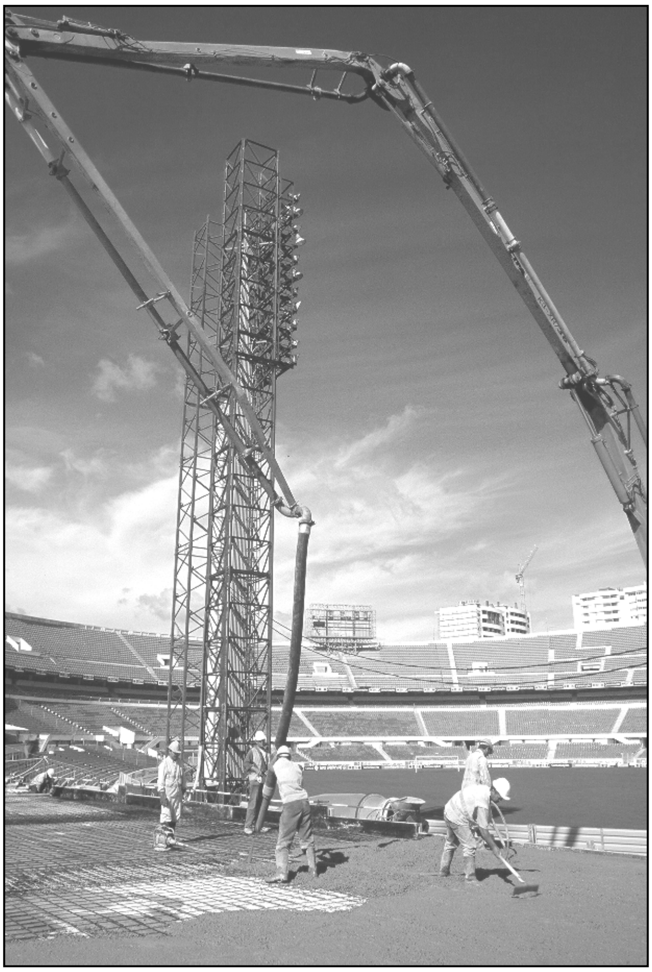

Figure 3: Work on new stadium proceeding with existing stadium in background

DESIGN CONCEPTS

So in March 2001, when Sinclair Knight Merz and HOK Sport were appointed to develop concepts for the new stadium, options for the design of the roof were one of the first aspects to be studied. Numerous ideas were developed. In considering the merits of each, the team assessed how the designs could be differentiated from other roof structures for stadiums around the world and how the designs of the other venues for Euro 2004 were developing. It is important that this design stands out as a unique and dramatic structure against the backdrop of the championships. Coupled with this the cost of the roof needed to be appropriate to the Client's limited budget and its construction feasible within the tight timescale.

The preliminary scheme developed was for a 30,000m^2 roof supported by four long span arches, curved on plan, spanning over the back of the stands and supporting roof diaphragms via fore and backstays. Uplift of the roof was resisted by a curved catenary cable between the springing points of the arch connected to the forestays. However this scheme was quickly optimised to bring it in line with the cost plan, since the separate structures for down and up wind forces was complex and expensive.

The improved final and rationalised scheme has the arches spanning up to 200m straight over the stands between the four 'corner' points of the seating bowl. The fore and back stays are tubular sections which can act as struts under wind uplift, hence negating the need for the catenary cable. This results in a simple structure with greater clarity and hence and uncluttered resulting architecture.

To add to the impact of the roof, the architect was keen to create a flat, thin edged roof so that the structure appears to hover over the bowl. The roof is to be extensively clad in transluscent material to add to the sense of lightness and bring daylight into the bowl. The large openings formed between the top of the seating bowl saddle and the flat roof over also allow plenty of air movement and natural light.

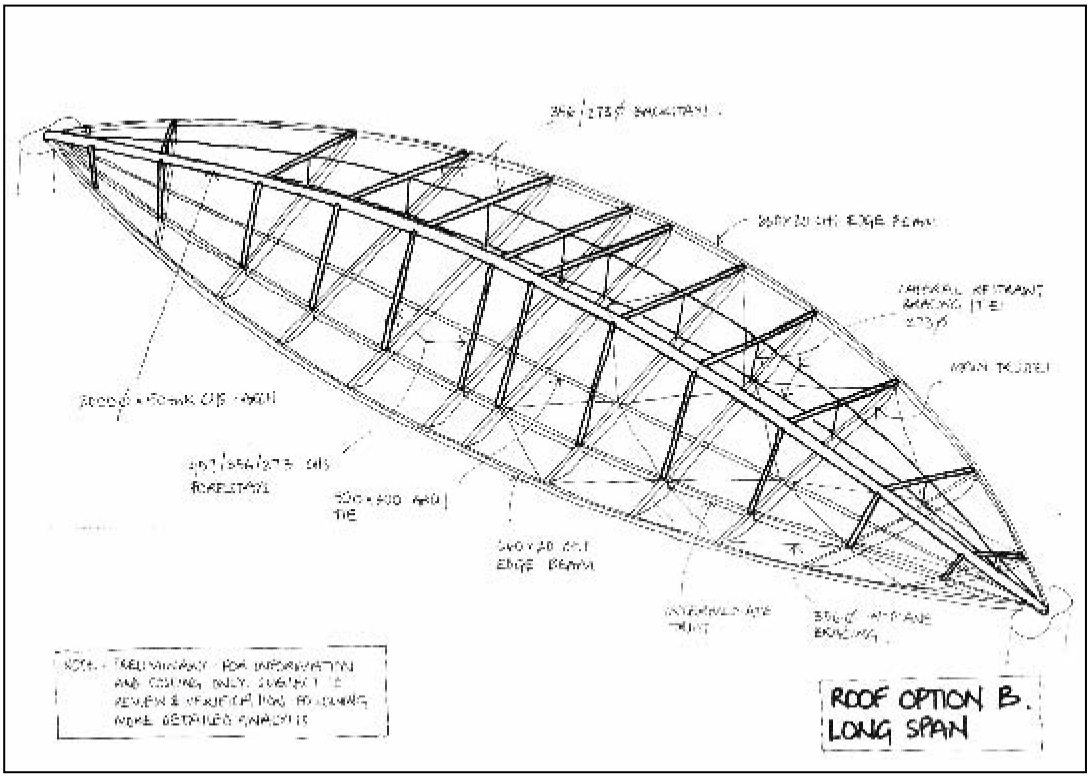

Figure 4: Scheme design for roof

In order to maximise this floating effect it is important that the supporting columns to the roof were as minimal as possible. Part of the strategy developed is to avoid resisting the arch thrusts at ground level, which would call for very bulky structure to transfer them down from the roof level which is almost 35m above ground level and 45m above the foundations. Hence the roof diaphragm is to act as a tie to the arch and the arch supports carry vertical and applied lateral forces only.

In exploring the concepts for the structure which would be required for this tieing action, an interesting visual effect was developed which will enhance the lightness of the structure desired by the architect. Separating the tie force from the entire roof diaphragm into a single tie member between the arch ends calls for some complex detailing, and for a sizeable member. To avoid this the entire roof structure is designed to act as a tie, and longitudinal members are curved on plan to focus on the arch springing point. It was decided therefore to curtail the inner edge of the roof to the outermost of these members. This creates a leaf shape to each roof segment which reduces the bulk of the roof structure in the corners (figure 5). In order to comply with UEFA requirements for covering the majority of the seats a roof covering was still required in the corners where the ends of the 'leaves' meet. An elegant lightweight 'eyebrow' roof supported off the main roofs was conceived for this clad in translucent material to increase the light brought into the stadium.

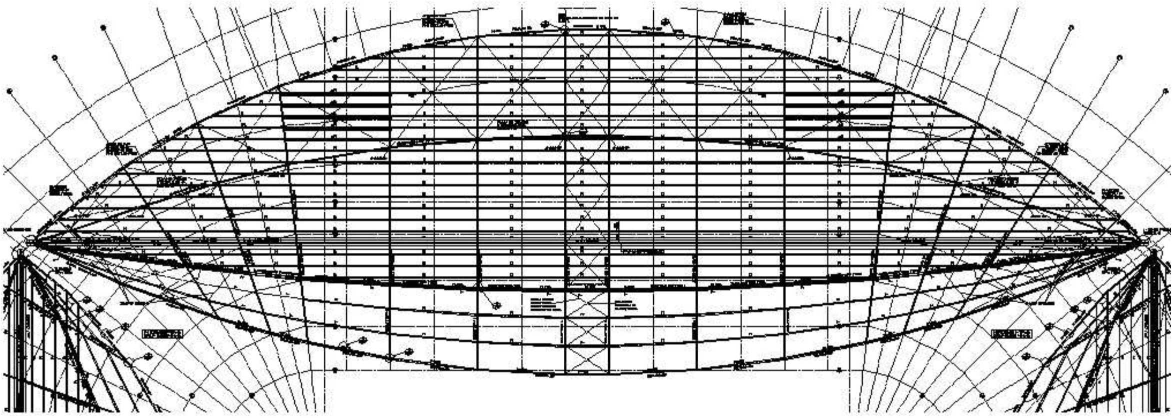

Figure 5: Plan on roof 'leaf'

In order to allow the roof diaphragm to develop the tensions to resist the arch thrusts, the ends of the roof needed to be allowed to move. One option considered for this was to incorporate pot bearings and allow one end of the roof to slide. This had a number of problems associated with it – primarily the cost of the bearings and the behaviour of the roof under earthquake. Under seismic loads directed along the length of the roof all of the load would need to be resisted at one end of the structure.

The alternative approach adopted was develop supports which were sufficiently flexible to allow the tie force to be develop, thereby negating the need for a sliding bearing. The height of the support facilitated this and relatively slender reinforced concrete 'supercolumns' were developed to fulfil this function (figure 6). These cantilever from the foundation at basement level and are completely detached from the main stadium structure for there entire height – i.e their sole purpose is to support the roof vertically and laterally. The supercolumns have the strength to resist seismic loads and transfer them to the foundations, sufficient stiffness to satisfy serviceability limits, but are flexible enough to allow the tie force to develop.

An added advantage to this is that the roof support system becomes flexible under seismic loads – essentially it can be considered as an inverted pendulum system cantilevering from the foundation. This results in a low natural frequency and hence low seismic loads, decreasing the size of the foundations. Under temperature loads the flexibility will also prevent large axial forces building up.

The only other supports to the roof are columns along the back of the seating bowl. To complement the design concept for the supercolumn these act as linkages i.e. they are pinned top and bottom. Hence they do not attract any lateral load and resist vertical loads only.

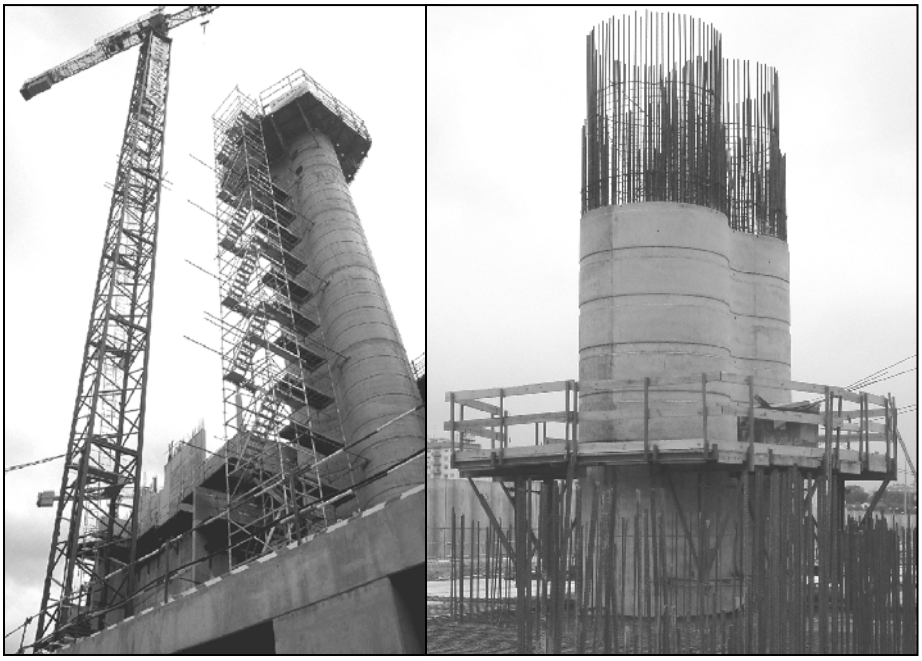

Figure 6: Supercolumn under construction

This overall design concept gave huge advantages for the design and construction of the stadium. The main stadium design and construction could proceed almost independently of the roof design (figure 7).

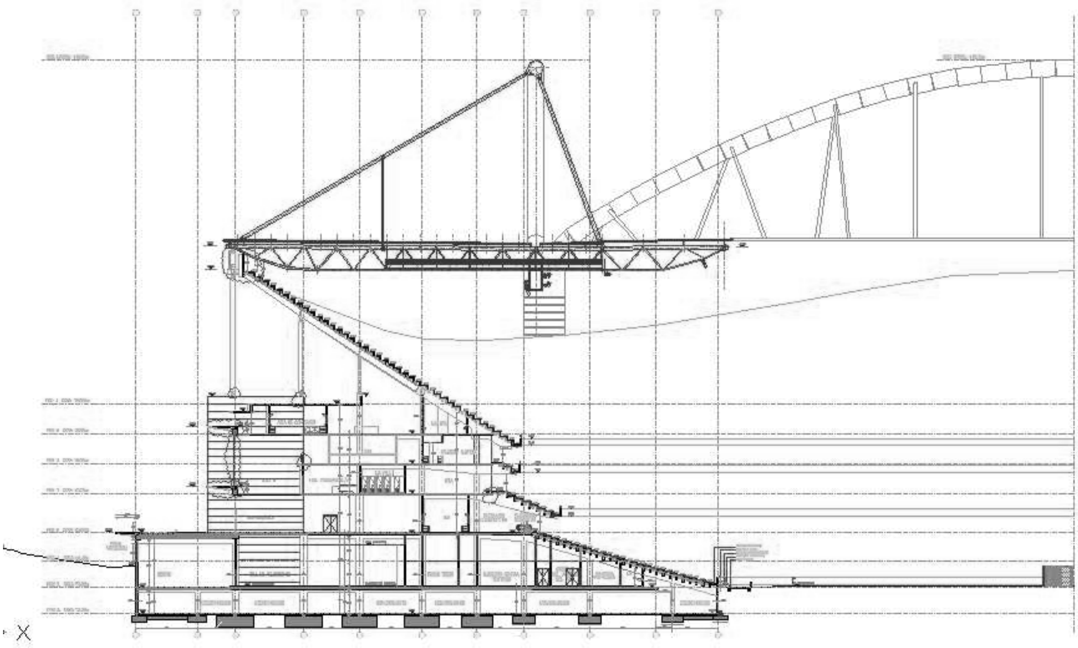

Figure 7: Overall section through stadium

The main information requirement at the early stages was for the foundations to the supercolumns, and an allowance for the loading along the back of the bowl but apart from this was possible to carry on with the optimisation the roof design whilst the main stadium proceeded to construction.

PROCUREMENT

The design team rapidly put together this workable scheme and concepts to enable the contractor to provide a firm price. A set of specifications and drawings sufficient to detail the clubs requirements were produced and used as the contract basis.

The Client was then able to negotiate a Guaranteed Maximum Price with the preferred contractor, Somague. The contractors price for the various construction packages were scrutinised by cost consultants Northcroft, who had worked with the design team from the initial concept stages.

Once the maximum price had been confirmed from the preliminary concepts developed, and funding was agreed in principal, the final approval lay with the members.

When it the time came to put the vote to the members assembly an estimated 10,000 people turned out. After a lengthy and emotionally charged debate between supporters, committee and board members the vote was put forward in the early hours of the morning. The scheme obtained an overwhelming support for the new construction.

Work on site started the next day in October 2001. Four weeks later the basements of the new stadium had been excavated and the first foundation poured.

DETAILED DESIGN

The design team was now novated to the contractor and with initial concept in place and the stadium superstructure construction proceeding, the aim was to finalise and optimise the design of the structural members, especially those in the roof plane.

Trusses span from the columns at the back of the bowl and cantilever off the forestays from the arch (figure 8). The total length of each of the trusses is up to 60m with a maximum 15m cantilever at the inner edge. The arrangement of these main trusses was dictated by their need for support, symmetry about the centre line of the roof and alignment with the structural grid.

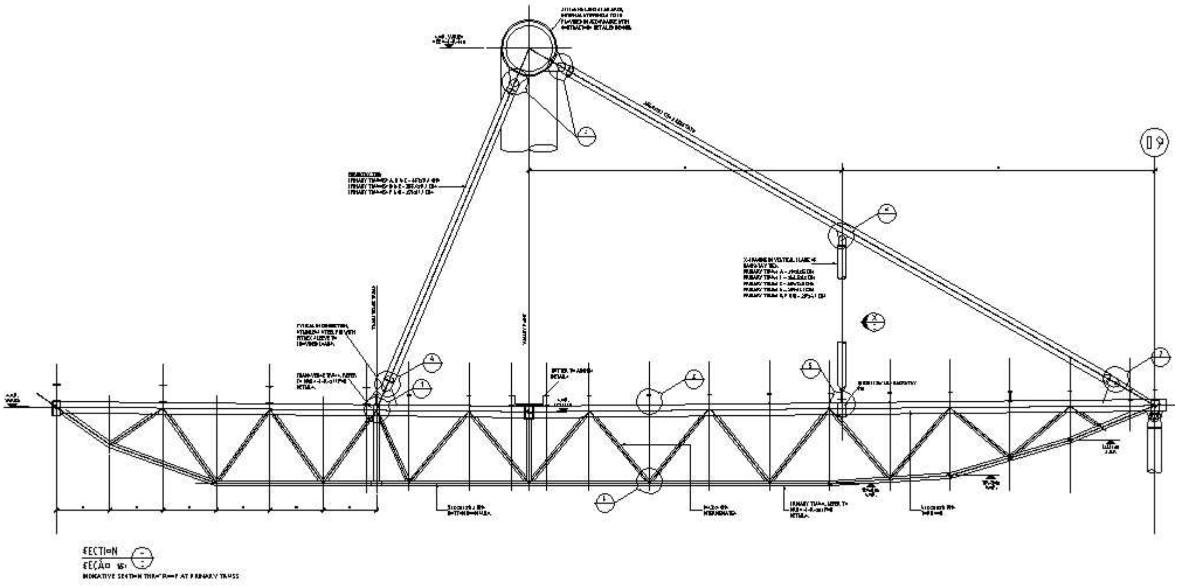

Figure 8: Section though roof

Many stadia roofs rely on a transfer truss between the columns and main trusses at the perimeter since the grid of the main trusses does not align with that of the seating bowl structure below. At the stage the arrangement of trusses was considered the seating bowl grid was fixed and therefore the generation of a structural grid had to be based on this. There was a desire to avoid the transfer truss solution partly due to the cost and also due to its bulkiness which would detract from the lightness of structure. A number of options were explored for different structural grids and column arrangements, including the use of V-columns, but eventually a symmetrical arrangement of main trusses spaced at approximately 15m c/c was determined which aligned with the structure below and allowed vertical columns to be utilised. Hence a transfer truss was avoided and the only structure required at the perimeter was a tie member.

The 2.5m deep trusses are planar to make them simple to fabricate. Top and bottom chords are fabricated from rectangular hollow sections with the bottom chord aligned with its minor axis for added stability against buckling in the wind uplift condition and on the cantilever ends. The bottom chords are also fly braced up to the purlins to provide the necessary restraint. Diagonals in the truss are circular hollow sections. This combination provides for simple detailing, fabrication and painting.

Supporting the trusses are the forestays and backstays, which also resist wind uplift loads. They are fabricated from circular hollow sections of varying diameter and are aligned with the trusses below. The forestays, which are positioned up to 15m from the inner edge of the roof, are set at a fairly steep angle and are relatively short. Therefore they are unrestrained along their length. However the backstays lie at a reasonably shallow angle and are much longer, and it was found that to minimise the diameter of the tubes a mid span restraint was required. This is provided with a strut and vertical braces down onto the roof plane.

There are a number of longitudinal members in the roof. At the perimeters large section rectangular hollow sections provide a tie/restraint to the trusses. A longitudinal truss is provided at the line of the forestay connection to the truss to provide torsional and lateral restraint to the truss at this point. A rectangular hollow section forms the main tie down the centre line of the roof. Finally a tie member is provided where the restraints to the backstays meet the trusses. All of these members are aligned with true arcs which coincide with the arch ends and ensure that tie forces converge, resultant in plane diaphragm forces are evenly distributed, and the configuration produces a good aesthetic.

Purlins are provided across the roof primarily to support the metal cladding system. Their secondary role is to restrain the top chord of the trusses and hence they are positively fixed between them. They are generally I-sections of 300mm depth spanning up to 15m and spaced at 2m centres. At the inner edge of the roof beneath the translucent cladding the purlins are spaced at 5m centres and are 600mm in depth. The purlins are provided with restraints to the bottom chord for the wind uplift case.

The cladding falls towards the centreline of the roof where the gutter is located. This was mainly an aesthetic requirement in order to maintain a thin edge to the roof. The top level of the trusses forms a true plane in order to limit any out of plane forces resulting from tie forces. At the design stage the roof plane was maintained on the horizontal and it was assumed falls would be accommodated within the cladding fixings. However the contractor was keen to economise this detail and it was agreed that the top chord of the trusses would be sloped to provide the necessary falls. The extra height of the purlins at the inner edge of the roof was utilised to provide an overlap between the translucent and metal cladding. The gutter is hung within the depth of the purlins and uses a syphonic drainage system in order that it can be flat.

Each roof ‘leaf’ is provided with in plane bracing which fulfils a number of roles. It allows the roof plane to act as a diaphragm to resist lateral loads and to distribute internal forces. It also collects restraint forces either from the fly bracing to the trusses or the ties to the purlins and distributes them back to the supports.

The 200m spanning arches are tubes of 2m diameter with a 40mm thick wall in grade S355 steel. They resist gravity and wind uplift forces and are pinned at each end to avoid the introduction of bending moments. In the initial design phase the shape of the arch was optimised according to the distribution of load to limit bending moments. The backstays provide the arches with resistance against buckling in the lateral direction. These horizontal forces are hence transferred into the roof diaphragm. Buckling in the vertical direction is resisted by the considerable bending capacity of the arch.

ANALYSIS

The two different ‘leaf’ types of the roof were modelled in three dimensions independently (figure 9). The structures were analysed on Strand 7.0, a finite element analysis computer programme. Even at the initial phases computer models were built of the roof to verify the understanding of the roof behaviour and calculations, and to optimise the design.

The final model incorporated all the structural members of the roof, including the purlins and the supercolumns. The purlins were required since they are fixed between the trusses and therefore attract tension/compression forces from the tieing of the arch. Restraints against buckling of these members under compression loads are provided by the restraints to the bottom chord and the roof sheeting. As a result of the analysis it was found that some purlins towards the springing point of the arch became overstressed and it was necessary to release the ends of these. Restraints to the associated main trusses are maintained by the purlins in the adjacent bay.

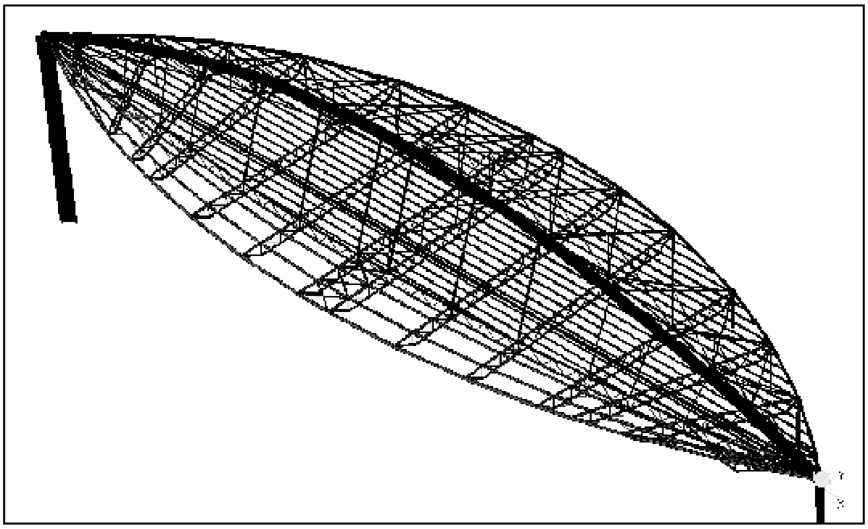

Figure 9: Computer model of roof

Non linear analyses of the roof were performed since movements of the roof are relatively large in magnitude comparison of linear and non-linear analyses showed that arch movements and stresses are amplified by non linear effects. To assess the potential for buckling of the arch and the whole roof, a non-linear buckling analysis was carried out. This gives a factor of safety against buckling for different modes of failure. The factor of safety against the first mode of overall buckling of the roof was found to be in the order of 2.7 on working loads. Based on our experience of structures of this kind a buckling factor of 2.5 is generally found to be sufficient and therefore we considered this to be acceptable.

Deflections of the roof were assessed from the results of the analysis. To account for dead load deflections, preset geometry values were determined from these results for the trusses, such that the roof plane will adopt the design geometry after application of the load. The effect of movements of the arch were allowed for in these truss presets, but the magnitude of the displacement of the arch was not felt to be sufficient to require the arch to be erected in a preset position.

Live load deflections are fairly small and the most onerous loading case was that of the wind. The overall movement of the roof is less important than local relative displacements which might cause damage to the cladding or cause ponding of rainfall run-off. The deflections were checked for this. Hence relatively high overall displacements occur which are not cause for concern.

LOADINGS

Loadings allowed for in the analysis of the roof include self weight, cladding, maintenance loads ($0.25kN/m^2$), lighting equipment, p.a. systems, gantry loads, video screens, temperature, blocked gutters, seismic and of course wind.

At the design stage an assessment of wind loadings was made to various codes of practice, including the British, Portuguese, Australian and Eurocode. It was found that the Portuguese code has an anomaly in it for downwards wind pressure on canopy roofs whereby extremely high wind pressures should be applied. From the assessment of the other codes and Sinclair Knight Merz's experience of such effects it was agreed that application of the Portuguese code, which is mandatory, would result in an over designed structure. It was therefore decided that a wind tunnel test should be carried out for the roof to determine actual wind pressures. However due to the tight timescale for the design and construction of the roof, the laboratory testing could not be completed prior to placing the order for the steelwork. So Sinclair Knight Merz used their judgement to ascertain a suitable set of design values and the wind tunnel testing was used as a verification of those assumptions.

The wind tunnel tests were carried out by RWDI in Canada. Aeroelastic behaviour of the roof was not found to be problematic and therefore a static model was used. RWDI produced a set of wind pressures for cladding and a set of overall pressures for the roof based on natural frequency modes provided by Sinclair Knight Merz. These pressures were all found to be within the design values used in the final design.

Temperature effects were applied to the roof with the range of +35°C/-25°C. As expected the flexibility of the supercolumns ensure the effects of this are minimal.

'EYEBROW' INFILL ROOF

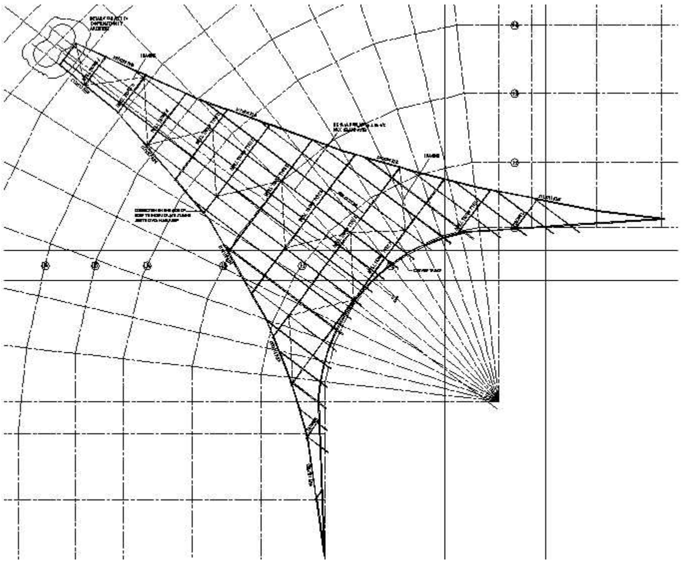

Figure 10: Plan on infill roof

The aesthetic requirements for the infill roofs between adjacent main roof leaves called for a light, minimal structure. The roof is to be set above the main roof to accentuate the different structures. The geometry of the roof is defined by a cylindrical surface tipped up at an angle. The main structural elements are elegant arched, tapering plane trusses in line with the circumference of the cylinder and hence their top chords are all of the same radius.

The trusses are formed with square hollow section chords and struts and tension member diagonals. Fly bracing provides restraint to the bottom chords against buckling in the wind uplift condition.

At the inner edge of the roof a curved truss trims the cylinder to the required shape of the perimeter. It supports curtailed trusses which are fixed to the curved trimmer truss such that they stabilise it against out of balance loads which would otherwise induce torsions.

Spanning in between the trusses are I-section purlins at 2m c/c. These support clear polycarbonate cladding, the setting out of which benefits from the pure geometry of the roof.

The intersection of the cylindrical geometry with that of the main roof produces a tapering vertical plane which is to be left open to allow light to flood into the seating bowl below. Square hollow section struts in this plane support the trusses of the eyebrow roof. Allowance has been made in the connections for the movements of the adjacent main roofs to ensure that the infill roof does not tie them together.

ERECTION METHODOLOGY:

The main contractor has employed the biggest steelwork subcontractor in Portugal to fabricate and erect the roof structure. The contractors strategy for the erection of the roof is to construct the arch in 15m long pieces off towers supported and back propped off the stands below. The design calls for the arch to be fully welded to ensure full strength and stiffness and therefore testing of the welds is critical in these locations.

The roof diaphragm is to be constructed off props off the stands and forestay and backstays connected. Where appropriate HSFG bolts are to be used to minimise the effect of bolts slip, for instance at the arch tie connections. Once the entire roof has been erected the structure will be carefully de-propped and finishes installed.

SUMMARY

The design and construction of this landmark stadium has been carried out to an extremely tight programme but the combination of the design teams’ stadia experience and a pro-active and enthusiastic contractor has meant that construction is running on time and on budget. At the time of writing the first sections of the roof structure are being delivered to site ready to be erected.

Whilst the aesthetic drivers in the design do not necessarily create the most efficient solution to providing a cover to a stadium such as this, the structure is nevertheless a lightweight solution, weighing around 115kg/m^2. The structural design has incorporated unique and innovative concepts not only to facilitate the procurement and construction but also to create a dramatic architecture which will be the focal point of international footballing championships in 2004.