Design and Fabrication of the new Wembley Stadium Roof

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On Thursday November the 16th, 2006

Background

The new Wembley Stadium was finally handed over to the FA in the Spring of 2007 and the first Cup Final was played in May 2007. Leading up to this, the project's difficulties have been well publicised with at least a year's delay, the budget significantly overspent and much legal action between the various parties. This paper is not about the rights and wrongs of how that situation came about but undoubtedly the complexity of build added to the cost and delays; it's also true that the skills of transforming a paper design into reality are not appreciated as widely as they should be in the structural engineering profession, so this paper concentrates on the practical difficulties of fabricating the roof and getting it erected to the state required by the design.

Structural form and components

The roof's structural form is shown in Figure 1 and understanding this is important background to understanding the erection sequence and its interdependency. The key components are the south roof plus the moving roof on top, the north roof, the cables supporting the north roof up to the arch (via the cable net) and the arch itself. Structurally the segments of the north and south roof are two way spanning but the arrangements are more complicated than that since the end trusses that span across the pitch (and carry the moving roof) also transfer some of the south roof load over the pitch and onto the north roof and thence up to the arch. Thus the arch actually supports a significant area of the whole roof.

In this respect, large parts of the roof are interdependent and are self supported when finished but unstable and unsupported until that final stage. Since the roof cannot physically all be erected in one piece, that means there are many intermediate stages that require propping and supporting until all the structural members are installed. Thus for example the purlins not only carry cladding onto the rafters they also restrain the rafters against lateral buckling and the rafters are not stable until the purlins are installed. As will be seen later, this is not as straightforward as it seems since roof deformations during construction effectively prevent the purlins from doing their job up until whole roof completion

The second key factor to be understood is linked to the scale of the roof and its flexibility (including cable extension). The roof is required to be in certain geometry under dead load. Reference to Figure 2 shows at the top row how each girder will deflect by sagging or hogging under applied vertical load. To achieve the correct geometry the girders therefore have to be fabricated with both positive and negative camber (there is actually some rotational camber as well). But the roof as a whole also sags significantly over the long spans and for example the attachment points under the cables will sag quite significantly as the long cables elongate under roof self weight load. To compensate for this, the roof has to be built artificially high (i.e. plus being pre-cambered) such that when it is released, it sags down into a correct shape. To give an indication of scale, a forestay cable 70m long will stretch about 150mm under permissible loading.

Unfortunately that degree of movement raises a second problem in that if the roof is built high, none of the parts actually fit together until they have been deformed by self weight stress and this poses a seemingly intractable problems to the contractor. It can only be overcome by building the roof high and then gradually lowering it and fitting it together sequentially as the parts are sequentially stressed and take up their correct shape.

This is an immensely complex operation and the way it is planned is to model the entire roof physically and mathematically in a computer programme and then 'un-build' it mathematically in the reverse sequence to construction. As this is done, the global roof positions at all the stages are revealed as is the geometry to which the individual members must be built. In real life, the roof is then built in that sequence and should all fit together. But the process is imperfect and to make it happen, various gaps and joints and articulations have to be built in to accommodate some of the movements that take place.

Arch Fabrication and Erection

The Wembley arch is the stadium's signature and one of the largest free standing arches in the world. It does have a structural function, that of supporting the north roof directly and of supporting much of the south roof (and the moving roof) indirectly. As the arch is so large, it had to be fabricated 'on the ground' and then be winched up into its final position which is leaning backwards away from the pitch. In the master plan, it was essential to build the arch first and then get it raised up the free the area underneath for the stadium construction. This in itself was a major operation of both construction and structural engineering.

A segment of the arch is shown in Figure 3, the sequence was to build the diaphragms first with stub tubes attached, then to place the diaphragms in position on the ground then to weld the tubes in-between, the amount of welding is very high and the difficulties of achieving alignment tolerance were significant. In its final condition, the arch is hinged 'in plane' at the base but to build it on the ground and raise it up, the arch had also to be hinged at 90o to this and so a rather complex doubly hinged temporary joint capable of rotation and capable of taking all the temporary forces was required at the arch ends. In its final state, the arch is held in place by cables and there are also cable attachment cleats for supporting the roof under. Thus there are lugs built in at intervals for cable attachment points. To cope with lifting and restraining the arch before completion, additional lugs were required.

The arch was lifted utilising five turning masts as shown in Figure 4. The longest mast was ~ 100m long and a substantial structure in its own right. The pulling forces were supplied by standard civil engineering strand jacks that have immense capability. One set of jacks was provided for each turning mast. As the jacks are activated, the turning masts rotate and exert a force on the arch causing it to be raised. Technically the force is controllable but the force applied to the arch is dictated by the stiffness of the particular attachment line. Moreover, because the lines are long they stretch a significant amount. This is important because it was not only necessary to lift the arch but also essential to maintain it in a plane during the lift to avoid dangers of buckling. To achieve both those objectives, the jacks were operated sequentially and the amount of jacking controlled by both force and displacement in a manner which lifted the whole arch but also kept it within planar tolerances. The whole operation was controlled by a 'Lift Master' and during the lift, surveys were conducted to assure that computer predictions matched reality.

The critical part of the lift was the stage at which the arch was turned through 90o. Up till then it could always have been lowered had something gone wrong but this was unlikely as the peak lifting loads took place at the moment the arch left the ground, so the entire system was in effect tested at that stage. In contrast, the first time the arch restraint lines had to work was the moment when the arch went 'over the top.' If they had failed then, the arch would have collapsed.

In its temporary state, the arch was held back on inclined forestay restraint cables

Erection generally

The erection of steel structures is not just a technical job it's a complex management process with implications in the supply chain all the way back though fabrication and procurement to design. Steel is required on site in the sequence necessary to erect it and that means every connection and every fastening and lack of any one part may well hold up the entire process. The key aspects to be taken account in assessing any erection scheme are:

sequencing
working area
assembly
lifting up
temporary stability
access
alignment and tolerances

Sequencing

The significance of the sequencing lies in the matters discussed in the introduction but thereafter there are implication for the flow of deliveries to site (and in turn the design and fabrication) and for buffer storage on site prior to erection.

Working Area

A substantial lay down area is required to assemble the pieces delivered small into site and then to link them together into the larger parts that might be required for completion. Figure 5 shows the pitch at Wembley during the peak construction activity and the image is of a forest of cranes and parts under assembly. Clearly there is little room to move and careful management is required not least since pieces must be pre assembled at locations where it is possible for cranes to reach at their permitted reach and capacity.

Assembly

It is frequently not possible to deliver parts to site in the lengths required for full assembly. Hence a sub assembly process is needed. The individual trusses at Wembley were long and can be described as semi veierendeel trusses with the bottom member being a stressed cable. To build these required that the top boom was placed on stillages, and then curved downwards whilst the cable was fitted into place on the bottom. This can be seen in Figure 6.

Lifting up

Craneage is expensive and capacity is limited by both tonnage and reach. Hence planning lifts is most important to assure cranes have adequate capacity and can be used efficiently. In a job like Wembley, which was not capable of rapid repetitive production, there are large amounts of down time whilst the cranes are not being used but still have to be paid for. This makes the 'craneage cost / tonne' quite significant. A second issue is that long structural members are capable of buckling under self weight if not restrained, so checks have to be made on the top boom stability for the loading case during lift.

Temporary stability

Long structural members are unstable and will tend to buckle unless restrained at intervals and this is normally achieved by framing steel members into the side for example in a roof this is normally the purlins. However, such steel does not exist either during the lift or immediately thereafter when the main members are initially positioned. Hence checks on stability are required and frequently, additional temporary steel has to be added

Access

Safety during erection is vital and one aspect of this is the thought and planning that has to go into assuring safe access provisions for workers to each location they are required to get to. Since it's clear at Wembley that workers have to travel along the rafters to fit purlins and to gain access to the front edge, significant temporary access ways were required. Moreover on a roof as large as Wembley, unless rapid access ways are provided, significant man hours will be lost just by getting to and from the work face.

Alignment

All structures have to be built to achieve alignment and tolerances. In simple structures, no fabrication measures are taken apart from traditional means of overcoming tolerance problems. In more complex structures, beams may be precambered and in frames, preset may be used. In really complex structures like Wembley, a combination of camber, preset and allowance for elastic shortening is required. Even so, the tolerance that might be achieved remains uncertain especially where there is large amount of welding since welding distortion is introduced. Particular care had to be allowed at interfaces with other disciplines so for example at Wembley, pessimism on the quality of alignment that could be achieved on the interface: moving roof to fixed roof, led to the introduction of significant articulation in the moving roof bogies to overcome anticipated problems.

Sequence South Roof

The south roof was erected by first building prop towers and temporary girders all along the front pitch side and then lifting the permanent trusses and spanning them in between. The complications arose by having to build the trusses high to accommodate anticipated sag in the front member. It also has to be appreciated that in the East West direction, the roof is a shallow arch and when such an arch sags, the lateral displacement at the ends is significant. To accommodate this, joints with longitudinal movement capability were deployed. But because the roof was built in the 'wrong shape' that meant none of the purlins fitted and by a significant amount. The implications of that were that the purlins were unable to do their job of restraining the rafter during the construction phase and so additional temporary stabilising steel had to be added. Reference to Figure 7 will show this was substantial.

The long truss running east west along the front of the south roof had a complex structural form with stressed cables at the lower boom. To construct it, the top boom with its hanging triangular props had to be built within temporary steel trusses spanning between the erection towers. The truss had to be built curved upwards, the bottom cable thread through and fixed and then as the whole roof was lowered via jacks, the ends of the truss eased back to their final position at the perimeter steel where final fixture was made. Due to the complex geometry, various 'hinges' had to be detailed in and then fixed up at truss completion.

Sequence North Roof

The erection plan of the north roof and the box beam on its front edge followed the same pattern as that of the south roof and the technical issues were largely the same. The only major difference was that prior to completion, the trusses spanning right across the pitch had to be terminated onto the front box member and the load transfer was significant. It will be seen from Figure 1 (structural form) that transfer of this load was essential to provide some of the balancing force to the arch to hold it in position.

Cable Net

The cables hanging from the arch down to the north roof and a pair of large horizontal cable spanning east west form what is known as the cable net. The load path for the north roof weight (Reference Figure 1) is up through the 'pyramids' across a joint through which the horizontal cables run and thence up the forestay to the arch.

An appreciation of the horizontal cable's function is important. These cables are not straight but actually have a catenary shape in space and the arch hangs on them when inclined, its weight being taken down the forestays and onto the cable and thence to the perimeter steel. However, as stated above when the roof is complete part of the inclined weight of the arch is balanced by loads from the north roof. Thus in a temporary stage, when the arch was held on the catenary cable alone, the load in those cable was higher than in the permanent stage and correspondingly the cable stretch was greater. Roughly the deformation of the cable in plan was about 250mm more at midspan in the temporary case than in the permanent case. This meant in turn that none of the trusses would actually fit perfectly in-between.

Arch transfer

A major activity was transfer of the north roof weight onto the arch via the pyramids, forestays and so on. The first stage was to release and adjust all the bundled up forestays so they hung roughly in line. The second stage was to pull the arch forwards so that the catenary cable could be drawn through its end supports (jacking was required); thereafter the arch was leaned back again, its load now being taken on the two catenary cables which duly stretched a commensurate amount. As the roof below would not entirely fit, a sequential loading / fitting process was required to apply load and fit up as the whole structure moved into its final position. This was possible by working from the roof centre outwards, fitting the front pyramid legs first then lowering the roof on its jacks to apply load and move the whole structure. As this jack down procedure progressed, the roof sagged into its final shape and the purlins moved longitudinally into their required position and could be sequentially fitted. All stages were predicted by computer analysis and constantly checked on site to assure that predicted movement matched reality

Moving Roof

The final major part of the project is the Moving Roof. A moving roof is required so that it can be retracted to aid growth in the pitch grass yet be moved forward to shelter the fans during a match. The moving roof consists of 7 sections; one large centre piece plus 6 outer pieces, 3 per side which can slide over each other. This arrangement requires that the panels are flexible out of plane to accommodate support structure movement and it requires that the roof panels move forward on bogies some of which are driven and some of which just guide and support. In recognition of potential movement in the underlying structures, articulation in plan, longitudinally and out of plane was provided in the roof panel connections to the bogies.

The whole roof is moved back and forwards on a rack and pinion system which provides very positive control and location. Nevertheless, to assure that the roof moves only as and when required, an electronic controls system with redundancy is included and the whole roof can be operated from the control room using a mimic screen.

Conclusions

Although there were trials and tribulations during the project, actually the work on site passed almost without mishap and high quality was achieved and the roof was built and it ended up more or less exactly as intended. That it did so is a testimony to the skills of the two steelwork companies whose engineers planned and made the parts, planned the erection and executed it. Those companies were Cleveland Bridge (Darlington) and Hollandia (Rotterdam) and it was a privilege for us to be associated with them. (Dr Mann worked as third party assessing the connection design and erection engineering during the Wembley Project)

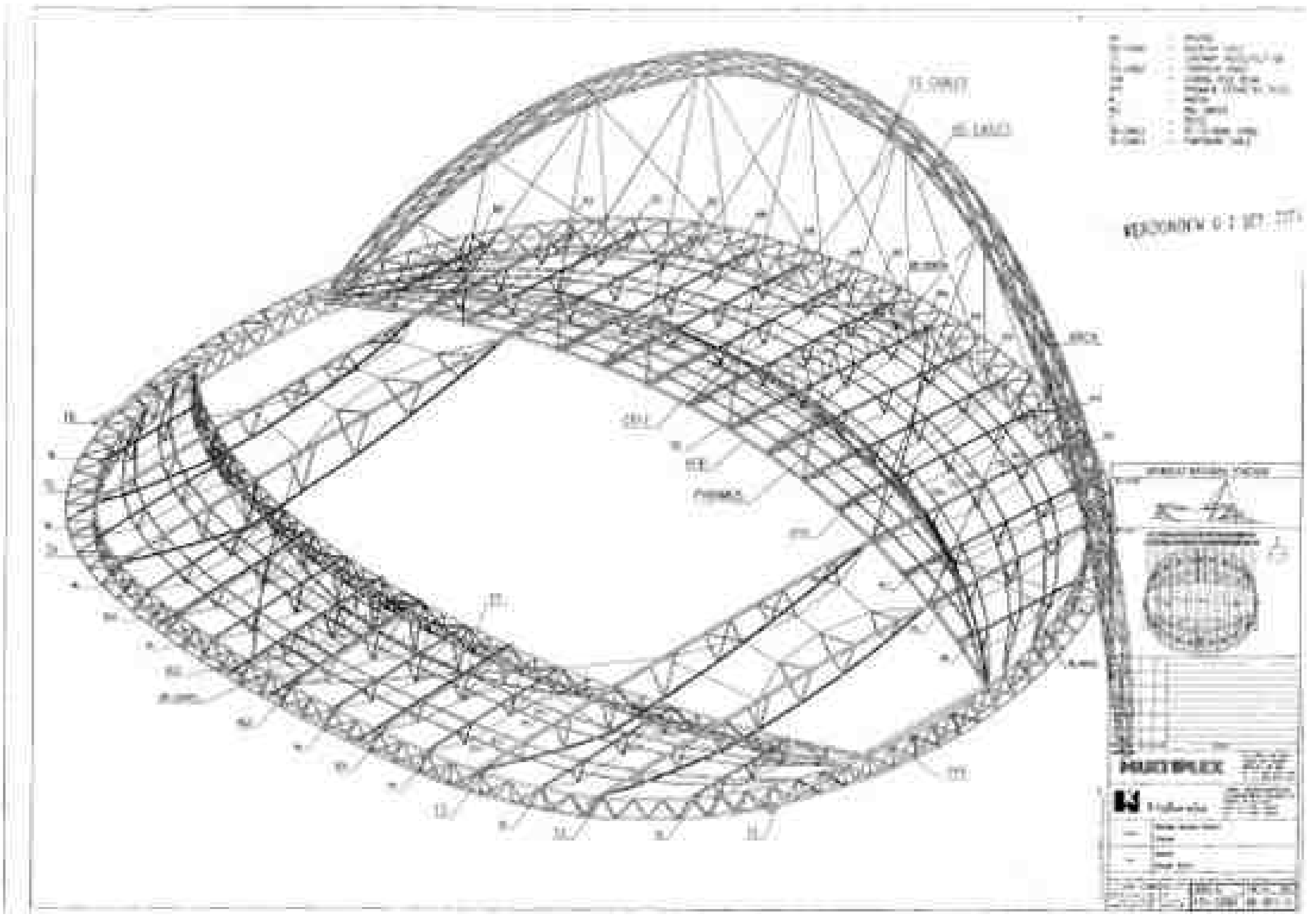

Fig 1, Structural Form

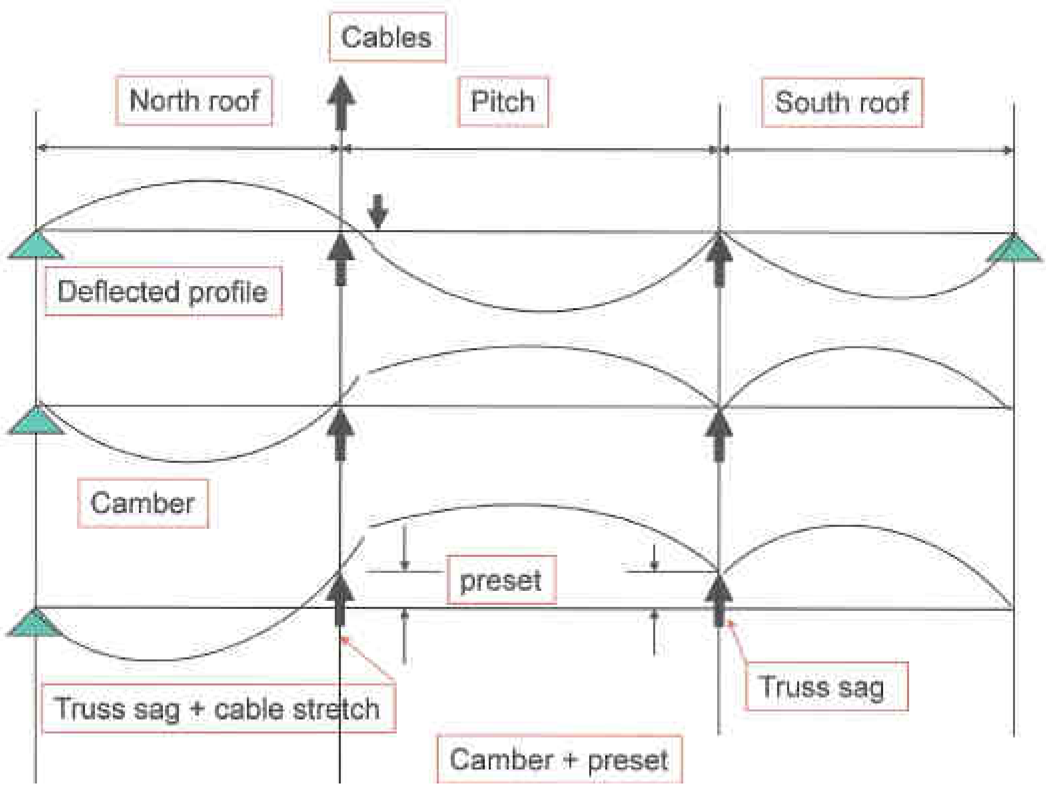

Fig 2. Deformations

Fig 3. Segment of Truss

Fig 4. Turning Mast

Fig 5. Crowded Pitch

Fig 6. Fitting Cables

Fig 7. Temporary Stability