



# An amphitheatre for cycling: the design, analysis and construction of the London 2012 Velodrome

**CLIENT:**

Olympic Delivery Authority

**ARCHITECT:**

Hopkins and Partners

**STRUCTURAL AND CIVIL****ENGINEERING:**

Expedition Engineering

**ENVIRONMENTAL AND****MECHANICAL AND****ELECTRICAL ENGINEERING:**

BDSP

**LANDSCAPE DESIGN:**

Grant Associates

**MAIN CONTRACTOR:** ISG**CONTRACTOR:**

Rock and Alluvium Piling

**CONCRETE FRAME****AND GROUNDWORKS****CONTRACTOR:** FDL**STRUCTURAL STEELWORK****CONTRACTOR:** Watson Steel**CABLE NET CONTRACTOR****(MANUFACTURE AND****INSTALLATION):** Pfeifer**CABLE NET DESIGNER****(FORMFINDING DESIGN****ADVICE, ERECTION****SEQUENCE):** Schlaich

Bergermann und Partners

**TIMBER ROOF CASSETTES****AND FAÇADE PANELS****CONTRACTOR:**

Wood Newton

**WIND TUNNEL****TESTING, WIND, SNOW****+ ENVIRONMENTAL****SPECIALIST ADVICE:** BMT**ROOF FINISHES****CONTRACTOR:** Prater**CATEGORY III CHECK:** Mott

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Figure 1  
Velodrome sitting in  
landscaped setting

Figure 3  
Pared down racing  
bike: an example of  
performance engineering

## Introduction

There is something rather deep-rooted about our desire to produce buildings choreographed to focus the attention of the spectator on the activities within. The use of a circular geometry to achieve this goes back a long way, from Stonehenge and Celtic stone circles to the Pantheon and the Colosseum, via Santa Maria del Fiore to St Peter's Square in the Vatican City, to bullrings, soccer stadia, athletics tracks and velodromes. For example, in an experiment we carried out for BBC's *Secrets of Lost Empires* in the 1990s in which a moving roof was gradually pulled out over a bullring (which was standing in for the Colosseum), the change of perception away from the sky and on to the centre of the circle was remarkably powerful. The focusing geometry of the enclosed curved three-dimensional space having a direct effect on the emotional reaction of the spectator and no doubt the participants as well.

When the RIBA ran the design competition for the London 2012 Velodrome (Figure 1), Expedition directors Ed McCann and Chris Wise originally decided not to enter as it was thought the odds against success were too long. The Aquatics Centre team was already chosen and had been instrumental in raising the design flag during London's ultimately successful bid for the Games. The Olympic Stadium was being procured as a design and build project which naturally favoured those who had already completed an international class stadium under that procurement structure. But the Velodrome competition was very seductive, and as a London practice who would probably only get this one chance to design an Olympic venue in our home city the call was eventually too strong and so we decided to enter. In the end about 100 teams made submissions, many highly gifted, many professional and personal friends, and all of whom we determined we would do our damndest to beat. It became a sporting competition for us too. So we threw our hats into the ring with Mike Taylor of Hopkins Architects, with whom we had an excellent collaborative relationship having come very close to pulling off the closest thing to a space station on earth with the Halley VI 'walking' research bases in Antarctica. For sustainability and environment we chose Klaus Bode of environmental designers BDSP with whom



"The Velodrome is really a simple building, the embodiment of Vitruvius' 'firmitas, utilitas, venustas'"

we had originally worked on the green high-rise prototype Commerzbank in Frankfurt and the "Stirling Prize-winning" American Air Museum at Duxford. This was a powerful team on paper, and more importantly, we were all friends. Into that mix we added Ed McCann, an engineer with a philosophical bent, and Ed and Mike set about trying to understand everything they could about the project, meeting cycling groups, users and communities to imprint their DNA on the project.

Of course any velodrome has at least two target user groups; the world-class cyclists, and the spectators. However, for an Olympic velodrome, there is a third group, the world-wide television audience who see the action remotely and for the London 2012 Velodrome in particular, there is a fourth interested set of people. These are the members of the public and amateur cyclists who will effectively be the main users of the project for most of its life in its legacy stage, as it sits at the top end of the Olympic Park (Figure 2).

The Velodrome is really a simple building, the embodiment of Vitruvius' 'firmitas, utilitas, venustas'. These three words are usually translated as firmness; commodity;



delight, but 'venustas' actually has a much more sensual meaning, coming from love, beauty and fertility. In this context, especially for a sporting venue which is designed to heighten performance and passion, our aim when designing buildings is, as far as possible, to put ourselves in the minds of the users. For design of the London Velodrome, it was relatively easy to imagine being in the crowd, watching at home on television, or taking our families up to the Olympic Park in years to come to try out a track bike and have a coffee. But none of us are world-class cyclists, so it was fortunate that multi-gold medallist Sir Chris Hoy was on the competition jury, together with representatives from British Cycling and local cyclists from the Eastway Cycle Circuit. Lastly we felt a strong affinity and respect for the work of those in the Lee Valley Regional Park Authority who would eventually take over the venue and run the facilities for the local people and visitors. All of these people were instrumental in informing our sense of clarity about what would be appropriate for the project. Their involvement showed the value of allowing the project brief to be a design project in its own right... following the sentiments of the late Steve Jobs of Apple's and our





Figure 2  
Velopark in legacy format

Figure 4  
Early design concept sketches (image courtesy of Hopkins Architects)

own Ed McCann's design paradox that 'you don't know what you want until you know what you can have'. The important personal contribution of all these characters and many others is well covered in the Architect's Journal special publication on the London 2012 Velodrome<sup>1</sup>.

It is hoped that together with the article published in Architect's Journal, which considered the wider context of the building, this paper (focusing on the technical response) will give a fuller understanding of the building development.

### Design concept

One of the design team's key aspirations was the desire for efficiency in all aspects of the venue's design – including structural and environmental performance. Inspiration was not hard to find: the modern track racing bike being the epitome of high performance engineering design where its form resolutely follows function (Figure 3). The whole design team bought into this desire and passionately believed that this could only be achieved by ensuring a fully integrated approach to design.

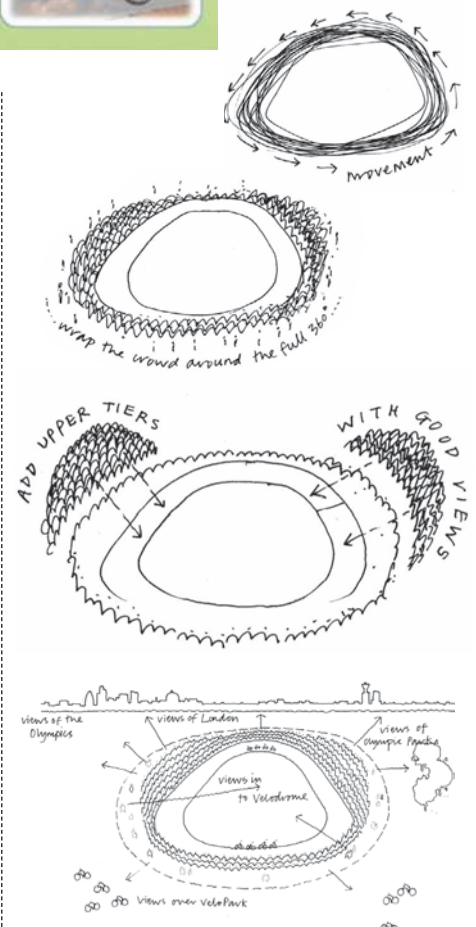
The form of the building is derived not from some whimsical gesture but from the considered process of piecing together all

the necessary accommodation around the cycle track. The track, which is the *raison d'être* of the building, was designed by specialist Ron Webb and has the following key statistics:

- 250m long FSC-certified Siberian Pine track
- 7m wide track with a 4m wide inner safety zone
- banking varying between 42° at the ends and 12° along the straights
- very tight stiffness and deflection criteria for the supporting structures

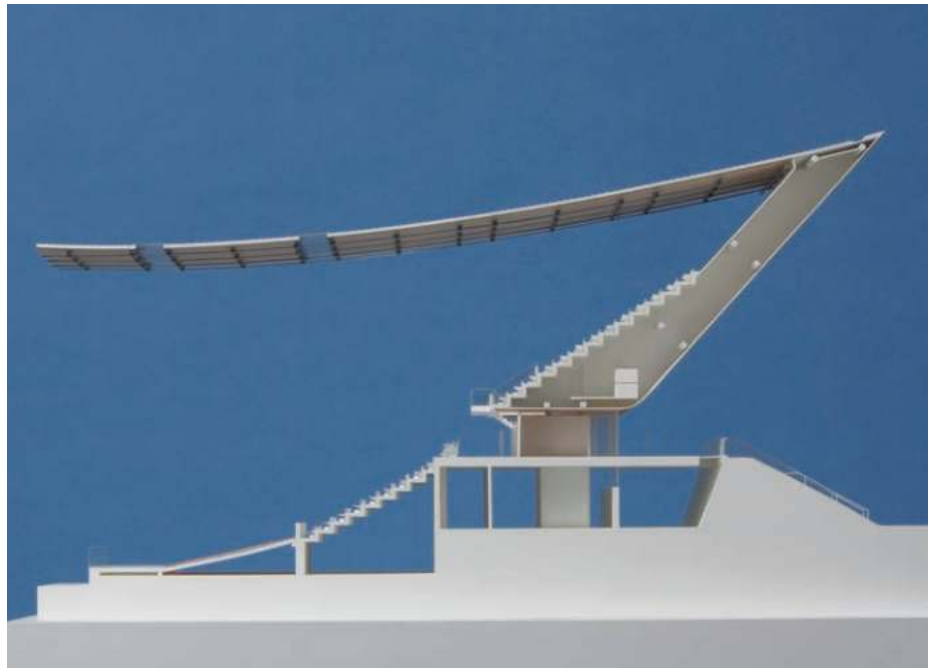
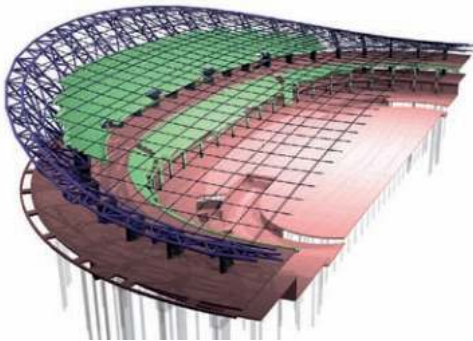
Packed tightly all around the track sits the lower of two tiers of seating, accommodating just under half of the maximum 6000 capacity crowd. Accessed from the main internal public concourse at its rear, the lower seating provides adequate seating for minor cycling events. The public concourse extends around the whole perimeter of the building, visually dividing the main arena horizontally into two distinct seating zones. The external façade of the concourse is fully glazed allowing views in and out of the building which surprisingly, is a rarity for velodromes (Figure 4).

Perched above and pulled as far forward as possible sit the upper tiers, intended to be used only for major events. The upper



● **Figure 5**  
Shrink-wrapping of façade  
onto structure

● **Figure 6**  
Integrated structure of  
roof tied into supporting  
bowl structure



tiers cantilever outwards beyond the extent of the lower concourse creating the large overhangs visible from outside. Due to the steepness of the track at the ends, the majority of the seating is concentrated along the straights where the best sightlines are enjoyed. Only a few seats continue around the tight bends and these are provided, at the request of the professional cyclists, to ensure that the atmosphere generated by the crowd continues around the track.

The external appearance of the Velodrome is the result of 'shrink wrapping' a skin onto the skeleton of accommodation within. This both minimises the internal volume that needs to be heated and reduces the surface area (and cost) of the cladding. The roof form is generated by tightly wrapping the form down onto the seating bowl – lifted up at the sides over the upper bowl seating and pulled down tightly at ends where the upper tiers are not present – leading to the distinctive double curved roof form. Similarly, the outer wall is inclined reflecting how the façade is tightly wrapped against the back of the upper bowl (Figure 5).

The Velodrome can be considered as being made up of three distinct structural regions; the roof, the upper bowl, and the concourse and lower levels. The three elements perform significantly different functions, which lead, within the context of an integrated building, to different structural responses.

#### The roof

## "The Velodrome can be considered as being made up of three distinct structural regions"

The size of the roof (circa. 13 500m<sup>2</sup>) means that it governs the structural response of the whole building. The environmental strategy required a deep build up of insulation, and planning conditions meant that a standing seam cladding system was necessary. From the outset, a cable net structure was the preferred choice as it lends itself perfectly to the shape and span, providing a combination of strength and lightness. Cable nets also bring programme and construction safety advantages, avoiding the need for scaffolding/temporary propping and vastly fewer operations carried out at height. Timber cassettes were selected for the roof infill panels: lightweight, readily prefabricated, with low embodied carbon and structurally appropriate for the spans between cable supports. The underside of each panel was finished in a birch-faced ply meaning that the internal finish was integral with the panel. One of the biggest challenges was deriving an appropriate system of support and articulation for the panels. The panels themselves are essentially rigid but are

supported off a relatively flexible cable net. In itself this is not a unique problem, but the additional complexity of having a relatively movement-inflexible standing seam roof on top meant that panel movements needed to be carefully considered and controlled.

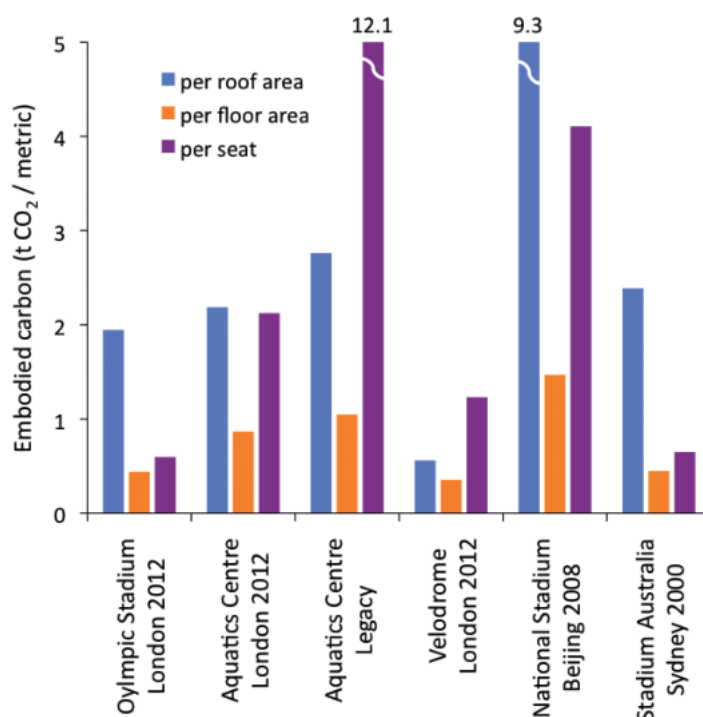
#### The upper bowl (and ring truss)

The upper bowl supports the upper seating tiers and is topped by a perimeter ring truss that is used to anchor the roof cables. The form of the bowl required an open skeletal structure to allow the integration of the air handling services, and also needed to accommodate the relative complex geometry of the curved bowl and ring truss. Construction issues included the need to make a large number of connections of bracing members, and a temporary construction loadcase where the self weight of the inclined bowl is in a counter direction to the completed state. For this reason structural UCs and hollow sections were selected.

#### Concourse and the lower levels

Much of the back of house accommodation is set below the public concourse and the dead weight of these structures and foundations are used to mobilise resistance to overturning resulting from the roof cable reactions. The size of the foundations changes significantly around the building, reflecting the variation in overturning resulting from the horizontal cable tensions. *In situ* concrete was used in these areas, with virtually all internal vertical faces and

Figure 7  
ODA comparison of  
embodied energy  
across 2012 (and  
previous Olympic)  
venues



soffits being left with a fairfaced finish to mobilise thermal mass and for economy and general robustness. This is discussed in greater depth later in the paper.

All foundations were piled reflecting the very poor shallow ground conditions. For higher loads under the main building 450mm and 600mm diameter CFA piles taken into the Thanet Sands. 270mm square precast piles driven into the shallower Terrace Gravels were used to support the lightly loaded infield and cycle track slabs.

### The unified structure

A key decision was made at the competition stage to rigidly link the roof perimeter ring truss to the bowl structure below. This ring truss performs the key role of being the element from which the roof cables are stressed – analogous to the rim of a tennis racket. Alternative arrangements where the ring truss was decoupled from the structure below were investigated, but in all options the total material requirement was far higher: the extra tonnage of steelwork in the enhanced ring truss massively outweighed the additional resources needed in the bowl and foundations of the base option. An additional advantage was that the ring truss was substantially smaller than a self-contained truss member would have been. This permitted a crisp detail at the interface of the roof and wall cladding (Figures 5 and 6).

Early in the design process, the economic viability of the cable net roof was questioned by the project cost consultants and,

together with the client's perception of additional risks introduced by its relatively rare construction methodology, the design team was instructed to adopt a more traditional form. In response, a variety of alternative forms were assessed, including timber and steel arches.

The project was procured using a two stage tender process, and the RIBA Stage C documents that formed the First Stage tender pack showed a steel arch scheme, with main arch member depths of circa. 1m. One of the shortlisted contractors, ISG, unaware of the previous schemes, identified a three month programme benefit with a cable net scheme and were subsequently awarded the contract. Over the course of a couple of months the design was significantly modified to accommodate the reintroduction of the cable net. The change was primarily a structural one, with the reversal of primarily roof load from the outward arch thrusts at the east and western ends, to inward cable forces on the northern and southern sides.

During this process, working closely with ISG's sub-contractors, Pfeifer and Schlaich Bergermann, the original cable arrangement was refined from more widely spaced large locked-coil cables to more frequent pairs of smaller spiral strand cables (36mm diameter). Due to the tight programme, the order for the cables had to be made very early in the process – three months after the switch back to cables was confirmed. The cable spacing was determined by the capacity of the largest diameter spiral

strand cable manufactured by Pfeifer. This was typically 3.6m spacing, which worked well with efficient spans of the infill panels and roof light sizes. In November 2008 a production slot for 16km of cable was reserved for the project.

### Designing sustainably

Unlike the other major venues on the Olympic Park, the details of the Velodrome's legacy use was known from the beginning of the project and was not dissimilar to the Games brief. This justified a much greater emphasis on the long-term use of the building with any modification for the games being considered a temporary overlay. This was assisted by the design team being commissioned not only for the full design of the Velodrome, but to also take in the surrounding Velopark (which included a BMX track, one mile cycle circuit and mountain bike trails) to RIBA Stage D. Therefore, the Velodrome was designed to be fully integrated into its future legacy setting (Fig. 2). London's Olympic bid promised that the 2012 Games would be the 'greenest ever'. The Olympic Delivery Authority (ODA) recognised that the venues would contribute to half the carbon footprint and, in response all venues were set tight environmental targets which included both operational and embodied carbon emission targets.

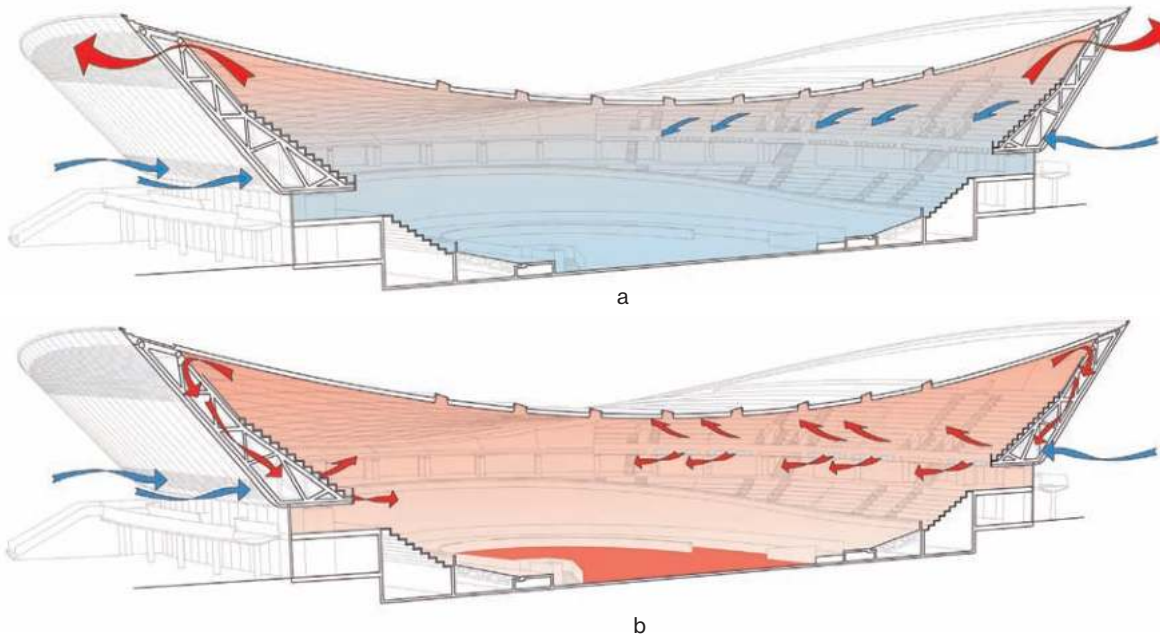
The Velodrome design team was keen to deliver sustainable design through a building based around true low energy design rather than reliance on state-of-the-art renewable technologies (in fact, the venue has no in-venue renewables). The resulting building easily surpasses the ODA targets and is generally acknowledged to be the most sustainable venue on the Olympic Park (Figure 7).

In terms of operational energy saving this included the provision of an highly-insulated envelope, a naturally ventilated arena (Figure 8) and adequate roof lights that avoid the need for artificial lighting for the majority (circa. 80%) of its operation. The ODA required all venues to exceed the Building Regulations (Part L 2006) by 15% through energy efficient design; the Velodrome exceeds Part L by 31%.

Embodied carbon presents a more interesting challenge: targets typically aim to lower the embodied carbon/t of material used rather than reduce the total quantities of materials used in the construction. With the idea of the racing bike in mind, the design approach followed the desire for lean design throughout, putting the right material in the right places and removing unnecessary 'fat'.

However, connecting these strands was the project team's approach to integrated design. More than just good teamwork and





© Figure 8  
Environmental diagram showing a) summer mode using natural ventilation and b) winter heating mode (image courtesy BDSP)

© Figure 9  
3D modelling of upper tier to integrate services, terracing and structure was essential early in the process: a) overlaid model from building inside b) from outside during construction

collaboration, integrated design requires all parties to engage in 'whole building design' and needs suitable tools to support a process which is inherently iterative. As would now be common practice on projects of this profile, the use of building information modelling (BIM) was used widely, but this was underpinned by extensive use of more traditional forms of communication and investigation, e.g. sketching, physical models and component 3D modelling. A key advance was bespoke scripting that allowed dynamic linkages between the structural analysis models, 3D modelling packages (e.g. Rhino and Grasshopper), the BIM software (Microstation) and spreadsheets. This allowed rapid checks to be carried out, giving instant verification of the effect of changes, from overall geometry to changes in individual elements, checking roof panel movements, spectator sight lines (C values) and member stresses. See Figure 9 for an example of integration of services and structure.

Lean design needs an appropriate response to the environment in which the building sits. A full appraisal is beyond the scope of this paper, but examples include the following:

#### Understanding the site and environmental loads

Like much of the Olympic Park site, the soil at the site of the Velodrome was contaminated as it had previously been the old West Ham tip. An enabling package designed and commissioned by the ODA left the site remediated but significant excavations were likely to extend below the marker layer into potentially contaminated soil. Therefore

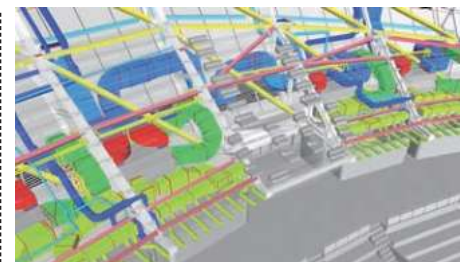
a number of steps were taken in order to minimise the impact of the building:

- the location of the Velodrome was modified from the 'planning cone' established in the Outline Planning Permission - in large part to reduce the volume of excavation required
- the enabling works finished ground levels were changed to reflect the developing foundation pile cap sizes and locations
- precast driven piles founded in the River Terrace Deposits were used for the infield slab (where loads were low but settlement deflections were very tight) to reduce the volume of excavated contaminated material
- an under-slab gas venting system was installed due to raised gas levels

Understanding the environmental loads is often a key requirement to ensure a lean design – and for the Velodrome this was paramount due to the size and lightness of the roof. Extensive wind tunnel testing was carried out, by BMT in Teddington, both on the completed building (with the proximity models reflecting both Olympic and legacy scenarios) and several stages through the upper bowl and roof construction. BMT also performed numerical modelling of snowdrift behaviour.

#### Understanding materials and structural behaviour

The continued tightening of Part L of the Building Regulations has forced designers to reduce the operational carbon emissions that has had the effect of increasing the relative contribution from the embodied carbon. Therefore, when considering 'low

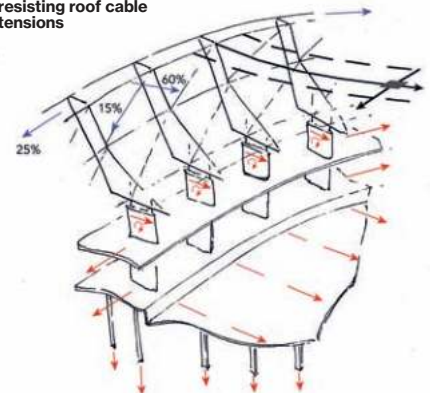


a



b

© Figure 11  
Four principal systems resisting roof cable tensions



	Competition Scheme 2007		Flat Scheme Early 2008		Steel Arch Scheme Mid 2008		Construction Scheme Early 2009	
MATERIALS	Mass	Embodied Carbon	Mass	Embodied Carbon	Mass	Embodied Carbon	Mass	Embodied Carbon
	kt	kt CO <sub>2</sub>	kt	kt CO <sub>2</sub>	kt	kt CO <sub>2</sub>	kt	kt CO <sub>2</sub>
Concrete	20.0	2.3	28.5	3.3	25.9	3.0	16.6	1.9
Reinforcing Steel	1.5	2.6	2.5	4.4	2.4	4.1	1.7	2.9
Structural Steel	1.4	2.5	0.9	1.6	1.0	1.7	0.8	1.5
Other	4.8	1.3	4.2	1.1	4.6	1.2	4.2	1.1
Total	27.6	8.7	36.2	10.4	33.9	10.1	23.3	7.4

Figure 10  
Comparison of embodied  
CO<sub>2</sub> at various stages  
in Velodrome design  
(reproduced from ODA  
Learning Legacy<sup>3</sup>)

## IMAGES



carbon' design, the role and influence of the structural engineer becomes increasingly important. The design response for the velodrome focused on the following areas:

- selecting materials for maximum performance – including weight, strength, stiffness, lifespan, thermal mass and embodied energy
- putting the structural material 'in the right place', i.e. lightweight design
- using elements for more than one purpose: for example, the precast upper seating tier units also formed the upper surface of an air plenum
- using modern methods of assessment (e.g. the recent Institution of Structural Engineers' report on crowd dynamics<sup>2</sup> to justify the building 'as is' rather than stiffening up the structure to achieve historic vibration limits
- low carbon material specification, e.g. specifying concrete with high cement replacement where high early age strength is not required (such as where the roof stressing operation was carried out six months after casting)

As part of the ODA's Learning Legacy project<sup>3</sup>, an estimate of the embodied carbon for the Velodrome was made. This study calculated the total embodied carbon, including both structural and non-structural elements at key stages throughout the design process, from the competition scheme to the completed building. The results (Figure 10) illustrate how the embodied carbon varied significantly throughout the process, and that traditional 'value engineering' does not necessarily sit well with 'low carbon' design.

## Analysing the structure

Following agreement to use a cable net in autumn 2008 the structural design progressed swiftly with start of construction in February 2009 and building completion in February 2011. Significant overlap between design, procurement and construction phases occurred for the first year of construction and the support of the team particularly highlighting the client and the contractor was invaluable during this time. A few areas of design development from this period are discussed below, focusing on the structural response to managing risk when working in the realm of the previously unproven.

## Whole building analysis

In order to resist the cable net forces using the full building, a clear understanding of the supporting structures was required, in particular how each part transfers and resists the forces from the roof.

The relationship between the shape of a cable, the effect of moving a support, and the tension acting within it is well understood. Assessing the flexibility of the cable supports, i.e. the stiffness of the building, was critical in ensuring both the shape of the roof (sightlines, weatherproofing) and the tensions (utilisation of cable forces, utilisation of supporting members) remained within acceptable limits. There are four principal systems to resist the roof cable tensions (and shown indicatively in Figure 11):

- A) Compression and bending forces contained within the slim-line continuous ring beam at the edge of the roof surface
- B) Compression forces locked within the

resistance of the 3D bowl through diagonal and horizontal bowl bracing members  
C) Bending forces in cantilevering primary trusses within the bowl steelwork, transferred to cantilevering post tensioned piers and resisted through compressions across the infield prop slab  
D) Compressions contained within the continuous concrete concourse ring slab

Figure 12 represents the primary loadpath C, in which around 60% of the roof forces are resisted.

Understanding the load in each system required a thorough understanding of each element and system stiffness in this highly indeterminate structure. In addition, a good knowledge of the building's overall flexibility was required to verify the roof response and therefore the envelope shape and shape of roof panels. If this response was stiffer or softer than predicted, the shape of items connected to the bowl and roof structure would be affected, while forces in elements may exceed allowances or cables go slack. The tolerances required in element shape and structural material would be excessive if a detailed study had not been carried out to provide confidence in the true and comparative stiffness of the building systems.

Sub-analysis models provided idealised properties for groups of elements (foundation and pile caps, infield slab, post-tensioned piers) as well as allowing for the investigation of the effect of stiffness variability. Examples included:

- additional stiffness in the upper bowl trusses through physical size of pre-welded connections

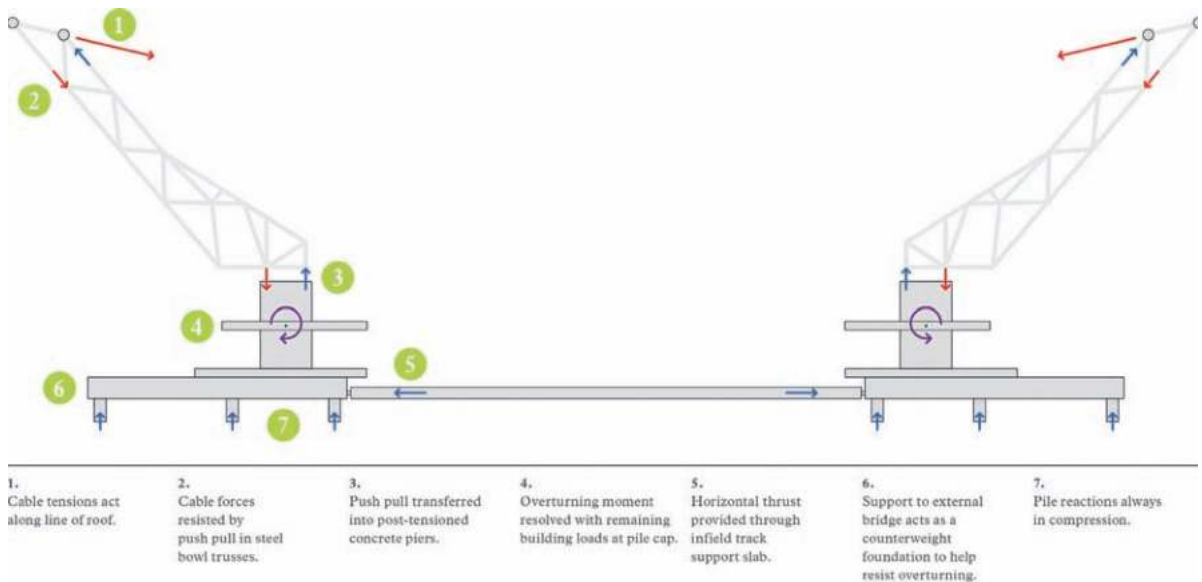


Figure 12  
Cut section  
through centre  
of Velodrome  
indicating primary  
force path

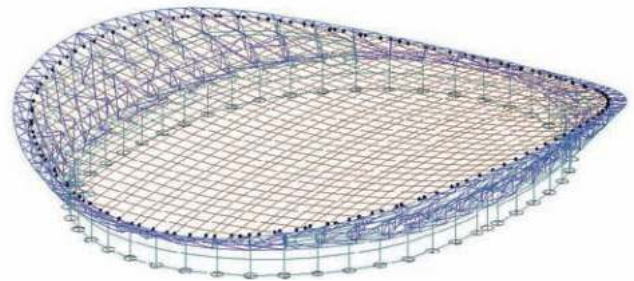
- tolerance on wall thickness in tubular bracing members
- variation of material properties
- variation in pile response causing change in rotational stiffness under concrete piers

A simplified stick model of the whole building (Figure 13) was used in analysis from design development onwards with stiffness properties provided by the sub analysis models. The sub analysis assessments of stiffness variation were statistically combined to produce worst 'credible' boundary conditions for the building. Analysis stages within the model gave results at three stiffness states: best estimate, least credible stiffness, and greatest credible stiffness. This detailed assessment provided improved confidence in the analysis and led to the envelope of 93% - 113% of best estimate of building stiffness.

The effect of this approach on the final position of the structure, and therefore on the following trades, was explained clearly to the full team including principal subcontractors. The construction set of steelwork drawings for the upper bowl showed an ideal position, as well as the envelope in which the structure may reside at the end of cable installation, allowing specialist subcontractors to detail appropriately for this range of positions (Figure 14).

Three independent reviews of the analysis work were carried out: one in-house, and two externally, one commissioned by Expedition (Graham Parkhouse as part of his dynamic review) and one by the client (Mott MacDonald CAT III review). This level of verification was appropriate given the reliance placed on the computer modelling

Figure 13  
Non-linear whole building  
analysis model with significant  
simplifications from sub analysis



and assessment in the final structural design.

Given that the predicted range of the vertical position of the roof centre varies from +110/-75mm due to building stiffnesses, credit is due to everyone involved, that following installation of the roof panels, the centre of the roof was measured as being within 10mm of best estimate position.

The analysis and design work could not have been so lean, and overlapping between architecture, mechanical + electrical and the structural side, without working in 3D. The concrete bowl was modelled fully using Microstation with the upper bowl and roof using Rhinoceros, allowing for the essential development and coordination within the design team and later specialist sub contractors. The whole building analysis model would not have been possible without the in house development of bespoke software to interact between GSA (Analysis software) and Rhinoceros. This allowed the analysis model to be updated simply and quickly each time the geometry of the building or elements were updated during the fast paced design development and early construction phases. This process also allowed for verification of subcontractor's fabrication 3D models for steelwork and

timber panels as conventional drawing checking could not be used on this curved building.

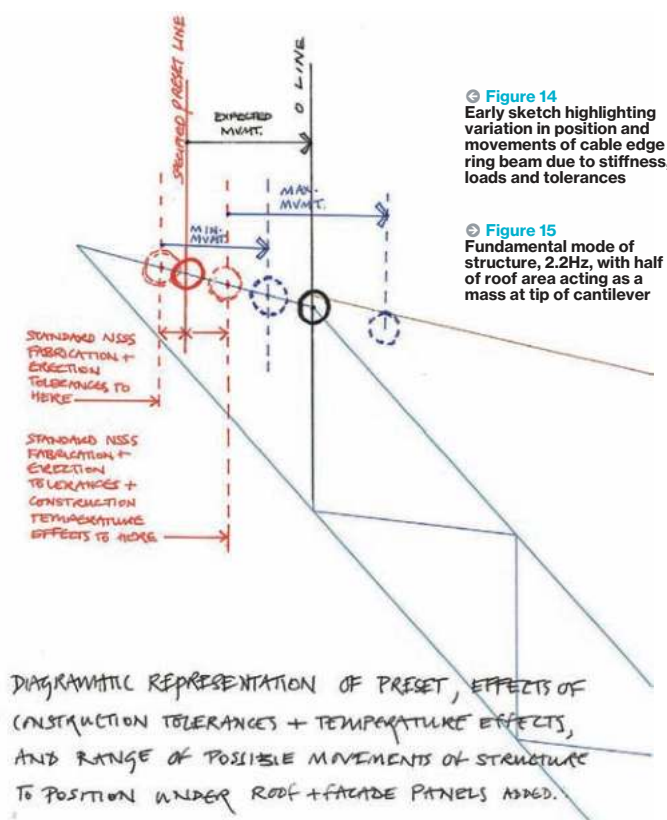
### Dynamics

The initial dynamic assessment of the Velodrome indicated the fundamental frequency of the stands was between 2 and 3Hz, a range deemed unacceptable in published guidance. All the Olympic venues were given access to the unpublished version of the Institution guide *Dynamic performance requirements for permanent grandstands subject to crowd action*<sup>2</sup> (published 2011) that advocates the use of performance-based design with inclusion of human-structure interaction effects.

Full details of the Velodrome dynamic analysis, including design criteria, FE modelling, time-integration procedure and validation procedures will be the subject of another paper; the aim here is to give an overview in the context of the wider design process.

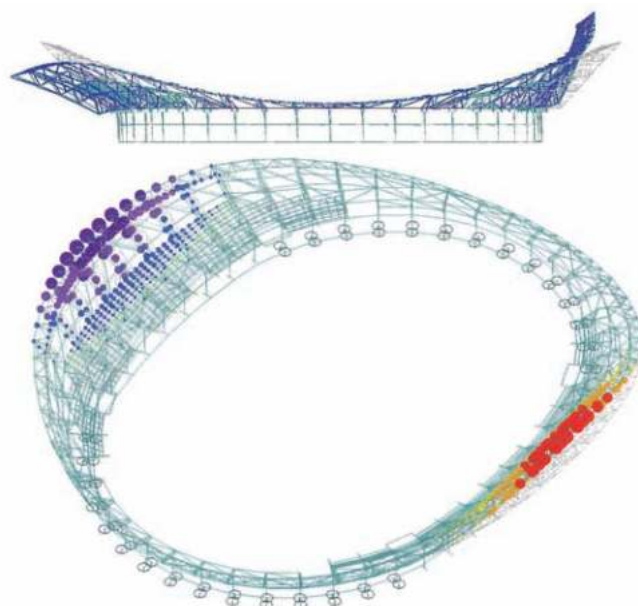
Dynamic assessment provided primary mode shapes of the cantilevered upper tier steel bowl and peak modal movements occurring at the cantilever tip (Figure 15). As the bowl seating runs to around half the cantilever length only, movements at the





© Figure 14  
Early sketch highlighting variation in position and movements of cable edge ring beam due to stiffness, loads and tolerances

© Figure 15  
Fundamental mode of structure, 2.2Hz, with half of roof area acting as a mass at tip of cantilever



most extreme seat are well reduced from the peak values. Using time-integration and human structure interaction theory, this analysis approach indicated acceptable accelerations at all seats.

Given the nature of the building and the use of new relatively untested guidance, three key risks were identified:

- the applicability of the building to the methodology
- the interpretation of the methodology and guidance
- the analytical model of the structure used to assess the modal response

A key risk was that the effect of the cable net roof on the building's dynamic response could not be accurately predicted; in particular whether the roof acts as a large well-damped mass or if instead only a small proportion of the roof is excited (this acting at the tip of the cantilever).

To reduce the risks to the project, Expedition commissioned an external strategic review of this dynamic analysis and approached John Dougill and Dr Graham Parkhouse – Chair and member respectively of the panel authoring the Institution report – to review the proposals. John provided a review of the applicability and choice of method, while Graham reviewed the analytical modelling of the building including material behaviour, assumed fixities and restraints, and in particular the modelling of the areas of roof engaged in the analysis. Additionally, Sheffield University was commissioned to provide an independent

verification of the in-house MATLAB program used for modal superposition.

If the client had not allowed the Olympic London venues to use this new methodology, the outcome for the Velodrome may well have required the inclusion of significant additional material to improve the stiffness and pushed the first mode beyond 3Hz. As such, the Institution Guidance<sup>2</sup> has had an extremely positive impact, and the work of the Institution's Dynamics Panel is gratefully acknowledged.

#### Gutter and roof drainage

The development of a single edge gutter to drain the 13 500m<sup>2</sup> roof – the area of 11 Olympic swimming pools – to only four downpipes, arranged two at each low end of the saddle shaped roof, was a complex and boundary-pushing piece of water engineering.

In a similar manner to the dynamic analysis, modelling within Expedition showed the validity of the proposal but acknowledged the lack of precedent. Again risks were reduced through the use of external specialists and testing, to carry out CFD modelling of the gutter and physical tests on the hopper. The design of the latter needed to move 95 litres of water per second into a 300mm diameter downpipe without causing any backup of flow, while fitting within tight curving façade boundaries. Both forms of testing provided confidence, and minor modifications to the scheme allowed this piece of novel technology to be

implemented. Importantly this design allowed the building to develop a crisp edge to the roof; a key architectural feature.

#### Disproportionate collapse

The design for resistance to disproportionate collapse considered a wide range of extreme, unusual and infrequent conditions causing an arrangement of loads outside of the design criteria used for the ULS design. For each scenario loading was developed, often combined with the loss of principal elements, and the resistance measured. Each scenario was first demonstrated not to cause collapse of the building, and where appropriate the resistance given. An example was calculating the substantial depth of snow that can be supported on the roof before cable failure is predicted.

The disproportionate resistance design was carried out during the detailed design phase allowing conclusions of the study to affect the final structural design. This approach was very useful in providing a review of the myriad of loading conditions occurring in structure with direction resistance, and provided a useful and robust basis for similar what-if discussions during the external CAT III review process.

#### Building a Velodrome

The Velodrome was the last major venue contract to be let and the first completed. ISG was appointed in the autumn of 2008 and engaged sub-contractors with proven expertise ensuring this fast and potentially complex construction would be completed safely and on time. For the design team, access to these subcontractors enabled the design to develop, with critical input from those responsible for manufacture and erection.

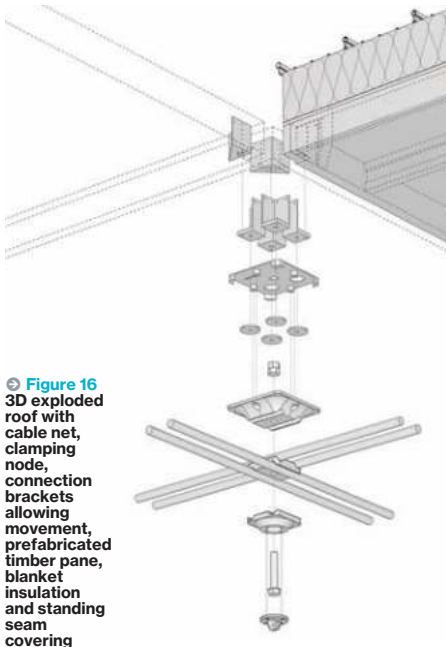
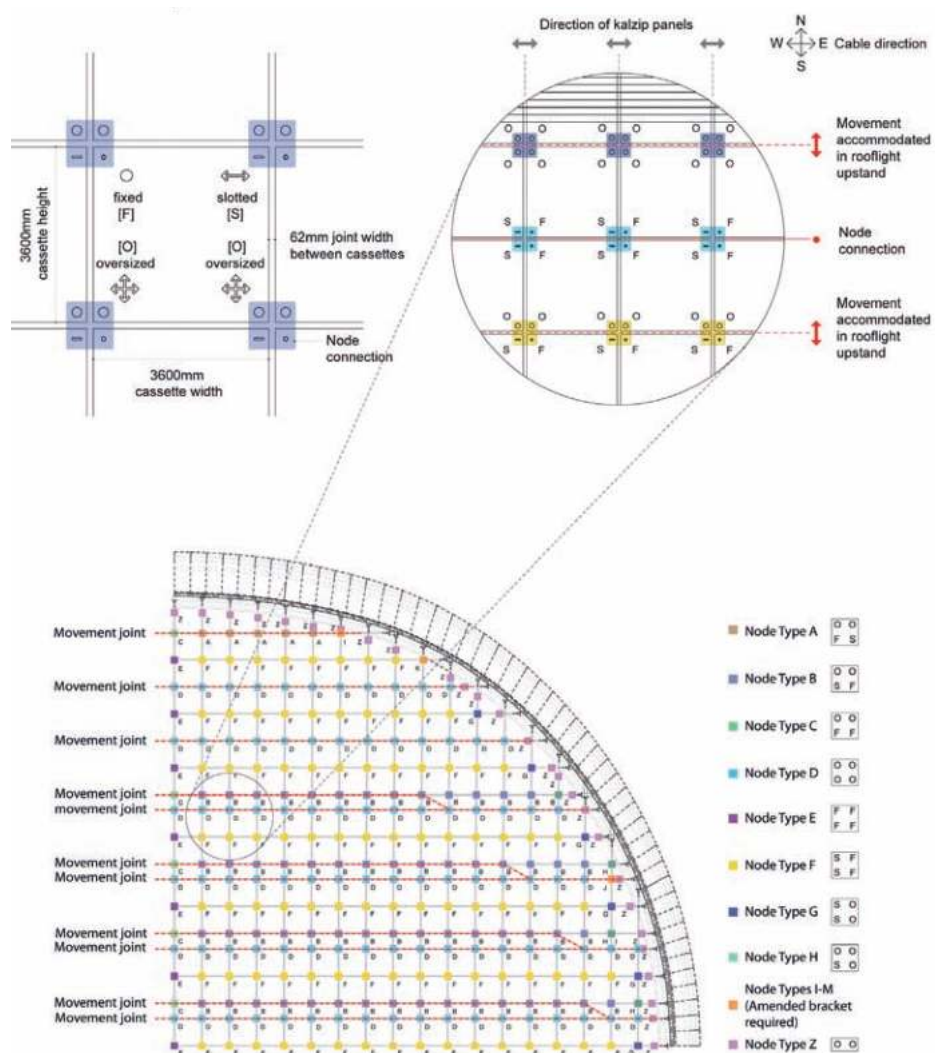


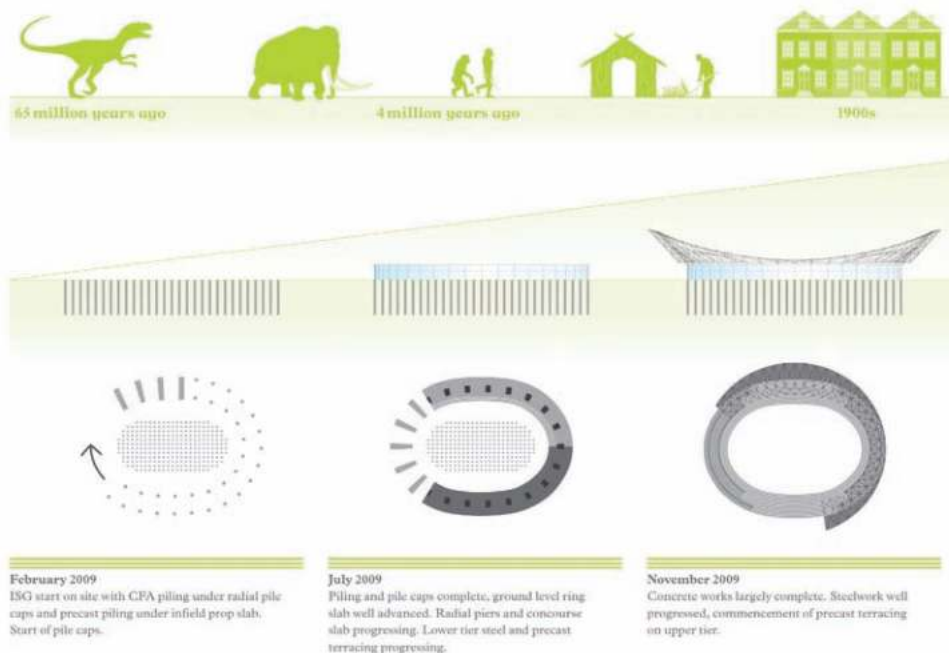
Figure 16  
3D exploded  
roof with  
cable net,  
clamping  
node,  
connection  
brackets  
allowing  
movement,  
prefabricated  
timber pane,  
blanket  
insulation  
and standing  
seam  
covering

Figure 17  
Diagrammatic representation of panel  
connection and movements (image  
courtesy Hopkins Architects)



ISG commenced piling in February 2009, three months after the adoption of a cable net roof and during the production of Stage E information. For the first six months the design, procurement and construction stages heavily overlapped. Although fast-paced and at times stressful, the significant benefit was the expert advice from specialist subcontractors during completion of detailed design.

The main building area requiring contractor input was the cable net and roof build up. Early meetings held with independent consultants Schlaich Bergemann and Partners (SBP) gave a better understanding of the challenges of designing and installing a cable net, and set the basic net parameters. As part of the design and construction team, SBP designed the roof node to clamp the cables together (its design governed by the forces arising during roof installation), and ultimately working for the cable net contractor, Pfeifer provided the final shape of the roof following installation. SBP and Pfeifer indicated that the net should be designed with only fixed end cables, i.e. without the use of turnbuckles to overcome site tolerance. The steelwork would need to achieve tight tolerances (around  $\pm 5\text{mm}$ ) at cable connection locations. The work of SBP both before and after Pfeifer was appointed, enabled the design team and main contractor to develop the cable net design with confidence of the roof's construction.





The most complex area of the project was the resolution, verification and understanding of the shapes and movements of the roof panels and build up above (Figure 16). The prefabricated timber cassettes made from OSB sheets and softwood joists support a thick blanket of insulation and a relatively inflexible standing seam roof, the latter a condition of planning. The provision of a relatively inflexible weatherproof covering on a large scale cable net apparently has little precedent.

The approximately square panels connect

to the cable net nodes using a façade-type arrangement of fixed, slotted and two oversized holes that holds panels in place on the sloping roof, but allows them to flex and breathe as the cable net extends, contracts and distorts (Figure 17). Panel movements are transferred to the standing seam where they are released at movement joints at each roof light, and at every 7.2m across the roof away from roof lights.

Simple, torsionally flexible 'bridging' panels are required at the edge of the roof to span between the relatively stiff ring beam and

the more flexible cable net. The standing seam could not accommodate these twisting movements and a deformable single ply membrane was used for the roof edge strip, a visual distinction that can be seen in the finished external envelope.

The shape of the roof panels is determined by the stiffness of the building, the symmetry of which is distorted by lift core positions, leading to the 1050 roof panels being individually shaped. A computational process considered the maximum oversized hole set by the roof node shape and reduced 1050 to just 19 shapes (Figure 18). The in-house software verified each panel could move as required and would not make contact with a neighbour, considering all fabrication and erection tolerances, the full range of cable net movements and distortions, and in a direction and rotation determined by the particular panel arrangement of slotted and oversized holes. This check was repeated at each limit of the building stiffness envelope.

The construction sequence is indicatively shown in Figure 19. The first six months of the construction included installation of the CFA piles and precast piles by Rock and Alluvium Piling, as well as casting of concrete pile caps, piers and ring slabs by FDL. Multiple concrete teams allowed for overlap between each area. Pour joints were introduced into continuous ring slabs and infield prop slab to control the effects of shrinkage. Fabricated curved steel shutters were used for the exposed radial concrete

Panel quantities:

Panel 01 = 53
Panel 02 = 30
Panel 03 = 16
Panel 04 = 14
Panel 05 = 15
Panel 06 = 12
Panel 07 = 12
Panel 08 = 10
Panel 09 = 08
Panel 10 = 04
Panel 11 = 29
Panel 12 = 2
Panel 13 = 5
Panel 14 = 12
Panel 15 = 1
Panel 16 = 2
Panel 17 = 9
Panel 18 = 1
Panel 19 = 3

Standardized roof cassette panel 1-19

Bespoke cassette pre-fabricated off-site

Make-up piece fabricated on-site

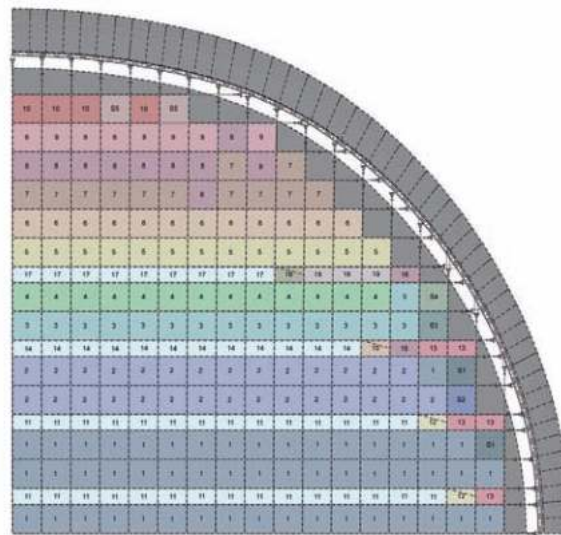


Figure 18  
Computational panel optimisation reduced 1050 panel shapes to just 19

Figure 19  
Construction sequence as experienced by site

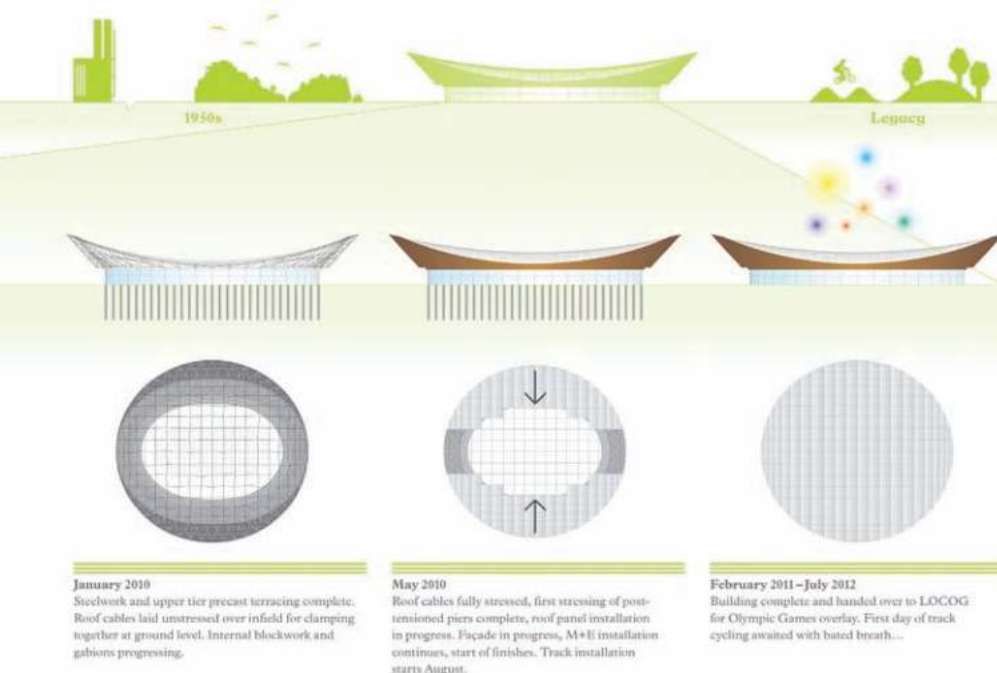


Figure 20  
Radial concrete post-tensioned piers



Figure 21  
a) Truss fabrication  
b) Site erection



a



b



a



b



c

Figure 22  
a) Cables laid loose over infield and clamped together at ground level  
b) Stage 1 of cable lift  
c) Stage 2 of cable lift – note slack cables in foreground

piers (Figure 20) to give a high quality of finish.

The steel upper bowl was fabricated and erected by Watson Steel as a series of 2D factory prefabricated trusses using off the shelf column sections and designed to be self stable on supporting piers following base bolt tightening. Lateral bracing forming part of the permanent works was used to tie the trusses together with no temporary steelwork required during the erection (Figure 21). Access to the specialist sub contractor during detailed design allowed splice positioning and key connection developments largely to be accommodated in final member design.

Expedition were commissioned by ISG to assess the construction sequence from the upper bowl onwards and provide support as this developed. This exercise allowed the overlap of the bowl erection with installation of the precast terracing, saving several weeks from the critical path. BMT carried out wind tunnel testing on three stages of construction, providing guidance for the preferred roof panel installation sequence. Analysis of the temporary forces arising from the cable installation indicated a small number of steelwork connections to be upgraded.

The post-tensioned concrete piers were designed for a number of load conditions with changing directions of moments during the construction sequence. Four 75mm diameter grade 1030 Macalloy bars per

pier are placed eccentrically to best resist ultimate bending moments and therefore careful balancing of forces and stressing was required throughout the construction sequence to prevent cracking and associated change in stiffness. Piers were stressed in two stages, each with 50% of final stress:

- after steelwork installation (pier moment turning out from the building)
- after cable installation, before roof panel placement (pier moment turning into the building)

The cables arrived on-site in January 2010 and were unrolled and placed in approximate plan position on the ground and lower terraced seating. Cable nodes clamped the cables together at precise factory marked positions and once complete the lifting of the net commenced as follows:

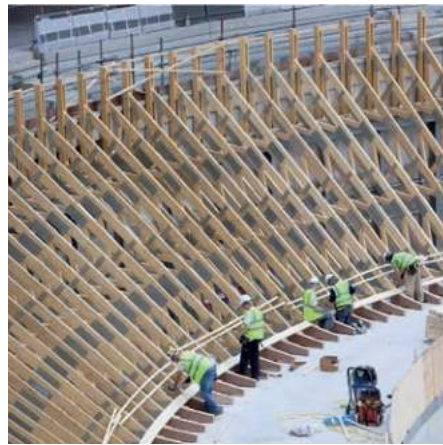
- Stage 1: one end of the central band of North South cables connected to the ring beam, the other end pulled into position using strand jacks as stresses are low and pinned
- Stage 2: stress the central band of the East West cables with one end connected, hydraulic jacks used from this point onwards to pull into position, pinned
- Stages 3 and 4: stress the edge cables in north south/east west directions respectively (Figure 22).

For the hydraulic jack stages, the jack load at cable pinning was recorded to

compare against detailed installation analysis undertaken by SBP using cable support stiffness (building response) information from Expedition. These results were appropriately close to predictions, giving confidence to the building modeling exercise. The erection of the net from unrolling to final jack removal took only eight weeks with the actual time spent lifting the net only two weeks of this period (Figure 23).

Following façade erection and weather tightness being established, the timber track was installed using closely spaced prefabricated timber trusses (Figure 24) which supported directly the square track units through nailing (and to each other).

Often aimed for and rarely achieved, the culture of problem resolution rather than proportioning of blame successfully established by ISG allowed the project to overcome problems encountered during the construction phase without detriment to the overall programme. Potentially the most significant was the positioning of the cable to ring beam connection brackets being out of tolerance. Through a combination of re-fabrication and installation, and detailed reanalysis of cable forces and panel positions, a solution was found requiring only 13 roof panels to be slightly modified due to shape changes of the net. Most importantly for such a visible project (Figure 25), the construction programme was maintained.



## Conclusions

The Velodrome has been well received by the client, the ODA, and also by the legacy user, the Lee Valley Regional Park Authority. The building is a combination of simple technologies that cumulatively have produced an exciting building with cycling at its centre (Figure 26). Structurally, the lessons the team has taken onboard for subsequent projects are:

- an increased use of testing, both physical and computational, provides confidence to the wider team when working in areas with little precedent
- where appropriate bring in specialists not normally on the design and construction team, and do not expect to be able to answer all design questions with the same attention to detail
- the time and effort involved in writing bespoke software can be easily justified

Ultimately, the building would have been very different had it not been designed and built by a truly collaborative team with all designers and contractors providing suggestions and solutions to all hurdles. For the structure, the relationship between architect and engineer was never so strong or so blurred – a bit like Sir Chris Hoy may be on his final approach to the line in August!

## Acknowledgements

Many people were involved in some form with the design and delivery of the London 2012 Velodrome. Companies which played a significant role in the design and delivery of the structural works are listed on page 13. For a full list of suppliers please refer to ref 1 and <http://www.london2012.com/get-involved/business-network/oda-suppliers/contractors/velodrome.php>

In addition, the contributions of John Dougill (ret.), Dr Graham Parkhouse (ind.) and Dr Paul Greening (UCL) in the field of dynamic assessment were significant.

Figure 23 Installation of prefabricated roof panels and gutter panels, reminiscent of boat building

Figure 24 Installation of track

Figure 25 Outside finished building looking across from bridge over River Lee



Figure 26 Inside completed building – Velodrome track under test

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