Delivering London 2012: the Velodrome

The 6000-seat Velodrome is host venue for track cycling during the London 2012 Olympic Games and Paralympic Games as well as the centrepiece for a velopark in legacy mode. As described in this paper, it is designed around optimal spectator and performance volumes, and every element was reduced to an absolute minimum so the structure and environmental services are as light as possible. This resulted in an innovative design, including a lightweight cable-net roof that reduced the embodied carbon dioxide content by 45% compared with a traditional steel structure and cut the construction period by 5 months. The energy performance of the building also maximises natural ventilation and use of daylight.

The Velodrome is one of the permanent venues to be built for the London 2012 Olympic and Paralympic Games and is located in the north of the Olympic Park in Stratford. After the games, the venue will become the centrepiece of a new ‘velopark’ alongside a re-configured Olympic BMX track. To these will be added a 1·6 km road circuit and 7 km of mountain bike trails, which will be owned and operated by Lee Valley Regional Park Authority (Figure 1). Schools, colleges, the general public and practising athletes alike will be able to use the facilities for years to come. A permanent velopark was a key

![Figure 1. The Velodrome will become the centrepiece of a new legacy velopark, with a reconfigured Olympic BMX track, 1·6 km road circuit and 7 km of mountain bike trails](image-url)
promise of London’s bid for the 2012 games. The site was previously home to Eastway Cycle Centre’s road circuit and off-road trails course, so one of the Olympic Delivery Authority’s (ODA’s) commitments was to replace and enhance these facilities after the games.

A competition for the design of the Velodrome and surrounding velopark was launched in February 2007, resulting in over 100 entries. This led to the appointment of a design team comprising Hopkins as architect, Expedition as structural and civil engineer, BDSP as service engineer and Grant Associates as landscape architect. Track designer Ron Webb was appointed directly by ODA. ODA’s brief for the Velodrome was for a 6000 seat venue that would provide top-class cycling facilities both for the games and in legacy, and would be a venue to inspire generations today and in the future. To deliver these expectations, ODA ran a Royal Institute of British Architects (Riba) design competition that included four-times Olympic gold medalist Chris Hoy on the jury. Hoy also provided subsequent input to the appointed design team from an athlete’s perspective as to what was important in creating a state-of-the-art velodrome. His insights ranged from providing seating all the way round and improving the intensity of the atmosphere for the crowd and the athletes to creating the right environmental conditions for record breaking and highlighting the importance of dedicated athletes’ toilets close to the track.

The key performance criteria

The key performance criteria for the Velodrome included the following.

- To be constructed on a site that partly overlies the disused West Ham refuse tip.
- To operate a 250 m long hand-laid timber track in a range of modes, from daily public practice sessions in winter with very low overall occupancy to a full 6000-seat arena for televised events in summer with elite riders (such as London 2012).
- To integrate fully into the London 2012 master plan (games and legacy) providing a key architectural ‘anchor’ for the north of the park.
- To be easily convertible after the games into legacy mode.
- To employ latest or first-principles design to maximise overall performance.
- To use manufacturing and construction expertise from the earliest opportunity.
- To have low embodied energy.
- To allow low in-use energy requirement – as an absolute minimum to perform at least 15% better than the Building Regulations 2006 part L.
- To connect to the park-wide district heat and power system.
- To achieve a Breeam sustainability assessment of ‘excellent’.
- To treat the design and construction process as one single collaborative exercise.

The conceptual response

The concept for the Velodrome was inspired by its future role as a hub for all forms of cycling within the Olympic Park. The conceptual challenge was how to form a symbolic and visual link between the indoor track and the range of external forms of cycling that would be on offer after the games including BMX, mountain bike, cyclo-cross and road cycling. Not only did the team want to break down the barriers between the various disciplines but it also wanted all of these activities to be immediately visible, including the indoor track, from the legacy park.

The formal response was very simple – the team split the 6000 seats in the brief horizontally so that half were around the perimeter of the track and the other
half were raised into the roof space (Figure 2). By creating this separation, the team was able to introduce a band of glazing around the spectator concourse forming a continuous ‘picture window’ between the internal environment of the 250 m track and the external cycle circuits within the park. The resulting concourse is a viewing gallery, where it is possible to watch over all the disciplines simultaneously. The architectural look of the Velodrome is of a minimal ‘shrink-wrapped void’ defined by an ethereal and transparent waistline. Working as an integrated design team, the team pursued an agenda of form following function. Inspired by the dynamism and geometry of the Siberian pine track and the engineering rigour of high-performance bikes, the team set out to design a building that made no distinction between architecture and engineering. The aim was for the resulting form to be lean and efficient, and to perform at the highest sporting levels in terms of function. It is designed around the minimum spectator and performance volume, and every element was reduced to an absolute minimum so that the structure and the environmental services are as intrinsically light as possible (Figure 3).

The upper bowl is an outward expression of the track since its geometry flows from the upper tier of seats that is, in turn, tightly wrapped around the track perimeter. The form of the building therefore echoes the sporting action within and becomes a manifestation of the energy and gravity-defying dynamism of track racing. It is intended to inspire future generations of cyclists as well as architects, engineers and clients.

Engineering design and analysis

Roof selection

The key innovation incorporated on the project was the roof. The initial stage design had a traditional steel roof. An alternative cable-net system was discounted early on as this was a relatively unused construction method in the UK and was therefore viewed as a construction and cost risk. However, the contractor, in conjunction with its specialist tier 2 supplier Pfeifer, suggested that the use of steelwork would have elongated the construction programme by 5–6 months and jeopardised the March 2011 construction completion date.

A study was commissioned into alternative roof systems, including a tensioned cable-net, compressive steel arches, glulam timber arches and a cable–timber hybrid system. From this, the cable-net roof emerged as the preferred option as, despite its relatively high capital cost, this was offset by the much faster construction programme. The virtual elimination of all scaffolding and temporary works effectively provided a cost-neutral, faster and less risky solution and was ultimately adopted. Overall, the programme was achieved in 23 months and completed 8 weeks ahead of the construction completion date.

Importantly, the cable net also gave a 45% saving in total embodied carbon dioxide in the primary structural elements over the steel-arch option. This was primarily achieved by the reduction in the roof steel weight from 1300 t to 160 t.

The contractor instigated a series of workshops that ran in parallel with the revised detailed design programme. The key to the success of the new roof scheme was having clarity on the lines of responsibility in relation to design and then allowing the specialist input to be integrated into the project at key strategic moments. This collaborative approach of the whole design team working with specialist subcontractors occurred throughout the project, with notable success on the tensioned cable roof but also on the structural timber roof casettes, the Kalzip roof and the external western red cedar cladding.

Structural concept

The pivotal design decision in the structure was to integrate the cable roof structure fully with that of the grid shell of the seating bowl, rather than allow them to move relatively independently of each other, as is usually the case for large stadia. This decision allowed the curved seating bowl to receive roof forces directly, either to carry them in cantilever action or to share and distribute them around down to the substructure (Figure 4).
The concept removed the need for the conventionally very large ring beam or truss at the edge of the roof. As a result, the structure only needed a minimal ring truss flush with the edge of the roof that could be laid flat to follow the roof curvature, giving the possibility of using the planar ring truss as a construction walkway, making use of it as a safe jacking gangway, allowing its use directly as a broad rain gutter and leaving a very crisp, sharp architectural edge to the roof on the skyline.

The cables forming the structure to the doubly curved roof are stressed against the perimeter ring truss, which is integral with the steel bowl forming the upper tiers. The roof is supported by pairs of spiral strand cables, each only 36 mm in diameter arranged in pairs at 3·6 m centres in both directions. The average weight of the cable-net roof system is an extremely efficient 30 kg/m², which includes cables, connections, end connection and also the minimal ring truss at the top of the seating bowl.

Due to the integral nature of the roof, ring truss and steel bowl, a ‘whole-building’ analysis model was developed and used extensively (Figure 5). A parametric approach was used to reflect the indeterminate nature of the structure, leading to a range of design forces and movements. Maximum cable tensions are estimated as being approximately 650 kN per cable and all cables were prestressed to remain in tension under all loading conditions. Because of the integrated structure, approximately 40% of the cable forces are resolved within the upper bowl and ring truss, while 60% of the cable forces generate large overturning moments in the substructure, which are resisted by the dead weight of the foundations. In addition, the...
track-level slab behaves as a plate, setting up a complete building system in equilibrium by distributing the horizontal forces from the seating bowl and roof system.

A major challenge involved designing the connection of the structural timber roof panels, which infill the gaps between the cables, to the cable net. These inherently inflexible panels had to adapt to the relatively flexible cable-net roof that supported them, while keeping relative movements of the delicate standing seam roof above within very tight range. In response, an articulated connection system was developed (Figures 6 and 7).

**Structural dynamics**

The dynamic performance of the Velodrome has been assessed using the latest procedures and guidance from the Institution of Structural Engineers (IStructE, 2008). The lowest mode that mobilises the seating terraces of the upper bowl was estimated as being approximately 2.3 Hz, well below the 3.5 Hz threshold historically seen as an acceptable lower bound.

The IStructE methodology uses spring-mass–damper body units to represent the effects of crowd loading and human–structure interaction. Using this method, the design criterion is to limit the maximum vertical root mean square acceleration to 0.075 g, which was easily achieved.

It is notable that a side study showed that several hundred tonnes of steel would have needed to have been added to the structure to bring its stiffness up to the traditional 3.5 Hz threshold, without tangible benefit to the occupants and with the great disadvantages of increasing cost, construction time, size and embodied energy.

**Substructure and foundations**

The Velodrome is located on a brownfield site on top of the old West Ham landfill site. The first 10 m is made ground, which is underlain by alluvium, river terrace deposits, the Lambeth Group, Thanet Sand and, finally, chalk. Much of this area of London was heavily bombed during World War II so the risk of unexploded ordnance led to each of the approximately 1000 pile locations being probed.

Approximately 600 of the piles are precast (270 mm x 270 mm, low-load, 9 m length), which removed the need for disposal of contaminated arisings and suited the light loading requirements of the infield slab. The remaining piles are open-bored and cast in situ, of which there were around 70 of 750 mm diameter and 300 of 450 mm diameter. They were installed to around 24 m depth, giving a 3 m embedment into the Thanet Sand. Sheet piles that were originally part of temporary works were incorporated into final basement wall design, bringing cost and programme efficiencies.

Building on a brownfield site posed additional challenges. The 10 m deep old fill emits methane that, if concentrated inside the building, could be problematic. The protection strategy was to wrap and seal the underside of the building in a gas membrane and channel gas though passive venting to the side of the building, where discreet gravel trenches disperse the gas.

The large overturning moments from the post-tensioned piers holding up the seating bowl needed to be transferred out at ground level. The ground was not suited to tension piles and so the structure has a ring of eccentrically placed large pile caps to counter overturning (Figure 8).

**Construction sequence**

A detailed staged analysis covering erection of the steel bowl, cable-net roof and roof cladding panels was carried out and required close coordination across the design and construction team. Wind-tunnel testing of the construction stages was commissioned from BMT to guard against misbehaviour of the part-clad roof under significant uplifts and local wind pressures.

The cable net was laid over the concrete seating bowl and jacked into position from the ring truss (Figure 9). Safety netting was suspended beneath, ready for installation of the drop-in timber roof cassettes.

A cable erection sequence for the cable net was developed by Pfeifer in conjunction with ISG and Expedition. In general, the construction stage forces applied to the permanent structure were within the design forces, but in several locations it was found necessary to increase the capacity or add a small amount of kentledge. During erection of the roof, installation cable forces were measured and compared against the analysis model – good agreement was achieved with the theoretical values.
**Sustainability**

**Materials**

The Velodrome design sought to optimise the use of materials and minimise the environmental and social impact of the materials that were specified. One of the most visually apparent materials used, externally and internally, is timber – a natural, replenishable material that was 100% legally and responsibly sourced (Figure 10).

The lightweight cable-net roof is a significant sustainability achievement. It significantly reduced the roof’s embodied energy by 45% compared with a much heavier traditional steel truss solution. Additionally, the use of 29% recycled content in the building (Figure 11), 98% responsible sourcing of materials and the use of ‘healthy’ materials such as water-based paints and form-release agents and adhesives with low volatile organic compounds contributed to the achievement of the sustainability objectives.

As with all Olympic venues, the Velodrome was required to reduce potable water demand by 40%. Half of this amount was achieved by the use of water-efficient fittings and half by rainwater harvesting to supply water to the toilets and landscape irrigation. On average, approximately 550 m³/year of water will be harvested: to achieve this, a tank of 25 m³ capacity has been provided.

**Environmental and energy strategy**

Cyclists need calm air at track level and prefer higher temperatures (26–28°C) as a lower air density means they can gain a few milliseconds and break records. However, spectators want to be much cooler. Furthermore, events lighting requirements are energy consuming and heat emitting, and there are restrictions on opening windows due to security and safety concerns.

Faced with these challenges, the project team adopted a holistic design philosophy of primarily minimising demand for energy as far as possible through passive measures. The building services engineering design focused on the needs of the Velodrome when in legacy mode while also meeting the more intensive needs of the games.

At Riba design stage E, the building design was 35% better than part L of the 2006 Building Regulations (a building emission rate of 39 kgCO₂/m²), significantly exceeding ODA’s 15% target and meeting the low-in-use energy objective.

The arena will be heated in winter, initially by underfloor heating, and supplemented by mechanical ventilation to achieve air temperatures applicable to use: typically 18°C for general use and 24–26°C at the track in training mode for professional cyclists. Whenever possible, external louvres set at high and low level in the facade will open to ventilate the arena naturally. Air recirculation will be used in periods of low occupancy (Figure 12).

Computational fluid dynamics analyses were used to show that, using passive means only, internal air temperatures will not exceed 3°C above external temperature during a summer event.

Windows and rooflights have been optimised to allow adequate daylight into the field of play and also into administra-
tion spaces, thus reducing dependency on artificial lighting energy (Figure 13). Typically, only 300 lux illumination is necessary for day-to-day use. Extensive studies were carried out to optimise the area and arrangement of the rooflights in terms of cost, weight, lux levels and uniformity. The high level of energy efficiency was achieved by placing sustainability at the core of the design from the outset. A combination of energy-efficiency measures work together as a complete, integrated solution. The venue is on track to achieve a Breeam sustainability assessment of ‘excellent’ in legacy, subject to some programme-wide initiatives being completed.

Implementation

ISG was appointed as principal contractor for the Velodrome project in June 2008. The basis of the design and build contract was an NEC3 Engineering and Construction Contract option C (ICE, 2005). The procurement was done in two phases with an initial target price based on preliminaries, overheads and profits. The team then worked to get to a final target price at Riba stage F, at which point the design team was then novated to the contractor. In addition, incentive milestones were introduced to drive delivery.

Good performance on the Velopark has resulted in an anticipated final cost of £102 million (including legacy transformation) of which £93 million is funded by ODA and £9 million is from external funding.

The revised programme targeted a project start date of February 2009, completion of stage E/F in March 2009 and contract completion in January 2011. Subsequent extensions of time due to resilience and weather took this completion date to February 2011. ODA held a further 3 weeks of float against the construction completion milestone (i.e. handover to the London Organising Committee for the Olympic Games (Locog)) on 11 March 2011.

Performance against the schedule for the Velodrome delivery resulted in early completion of the building on 13 January 2011, 7 weeks ahead of the baseline and 18 months before games (Figure 14).

Construction management

Construction of the Velodrome was a testament to delivering an iconic venue in a lean way by incorporating innovative solutions and maximising off-site fabrication. The critical path of the construction works ran through the structure, firstly for weathertightness and then watertightness. As such, the key focus of the team following substantial completion of the concrete works was completing the roof and cladding works.

The major elements of the roof work needed to get the building substantially watertight were installation of the cable net and roof cassettes. The cable net was installed in 2 months. Compared with the proposed programme of 7–8 months for a traditional steel structure, this was a key component in ensuring the overall build programme was achieved in 22 months.

The cable-net installation was broadly split into two distinct phases. The first phase was laying the cable at ground level while also attaching the roof cas-
sette node connectors to minimise works at high level. This took approximately 5 weeks. The second phase was the lifting of the cable net into its final geometry, including all final connection and testing works. This took approximately 3.5 weeks.

Following successful completion of the cable-net installation, 1090 roof cassettes needed to be installed in approximately 3.5 months. To add a degree of complication, works had to progress simultaneously on both sides so as not to destabilise the structure. This challenge was overcome and, at peak, one prefabricated roof cassette was being lifted from ground level and fixed into the node connectors every 10 minutes. In addition to this, the underside of the roof was prefabricated off-site with the finished birch-faced plywood. Therefore, with completion of the roof cassettes, not only had the building been made substantially weathertight but the finished roof for around 13 300 m² of the auditorium had also been achieved (Figure 15).

The cladding panels followed a similar process to that of the roof cassettes. The added complication on these was that almost all of the wall cassettes were different and their installation needed bespoke equipment due to the geometry of the Velodrome. This work was progressed over a period of 5 months to ensure that the building was fully watertight, thereby taking the western red cedar installation of the critical path.

Conversion for legacy mode

The essential requirements to create a venue for legacy are all contained within the initial concept. From the start, the team considered it more appropriate that the building was conceived for legacy and ‘converted’ for the games rather than vice versa. For example, the team included extensive rooflights to reduce whole-life lighting costs.

Working closely with local cycle groups, the team developed an intricate series of cycle circuits around the Velodrome and, where possible, included their construction in the base build. In the spirit of efficiency, one of the construction bridges across the River Lee was retained as part of the road circuit. The final implementation of these circuits is only possible when the games ‘overlay’ is removed and the legacy transformation can complete the Lee Valley velopark in 2013. The velopark will then be taken forward through the ownership and management of the Lee Valley Regional Park Authority who already have funding in place to subsidise the facility for the next 25 years.

Conclusion

While the project team might find it tempting to celebrate its technical wizardry, aesthetic touch or environmental subtlety, its defining overriding success was really good collaboration. Often claimed but seldom achieved, this is the feature of the project that has allowed everything else to see the light of day. If such collaboration could be replicated as a matter of course elsewhere, many other apparently intractable problems would perhaps turn out to be nothing of the sort. The project has been well received so far and was handed over to games operator Locog in February 2011.

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- ODA (client)
- CLM (delivery partner/project manager)
- Hopkins Architects (architect)
- Expedition (structural engineer)
- BDSP Partnership (mechanical electrical plumbing engineer)
- Ron Webb (track designer)
- ISG (main contractor).

The key specialist suppliers were

- Pfeifer with Schlaich Bergermann (cable net)
- Kalzip (roof covering)
- Watsons (structural steel)
- Foundation Developments (concrete substructure and superstructure)
- Wood Newton (roof cassettes and external timber cladding)
- Rock & Alluvium (piling).

References


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