Essential Elements

BY KEN JONES

London's new O_2 Arena uses a steel roof, erected with an innovative lifting operation, to top what was designed to be Europe's most acoustically advanced concert venue.

THERE'S BEAUTIFUL MUSIC COMING FROM GREENWICH, LONDON. More specifically, it's coming from the new O_2 Arena. Built within London's existing Millennium Dome structure, the recently opened arena provides London with a 22,000-seat state-of-the-art entertainment venue. Designed to be the most technically and acoustically advanced concert arena in Europe, it also plays host to multiple sporting events.

Geometry and Design

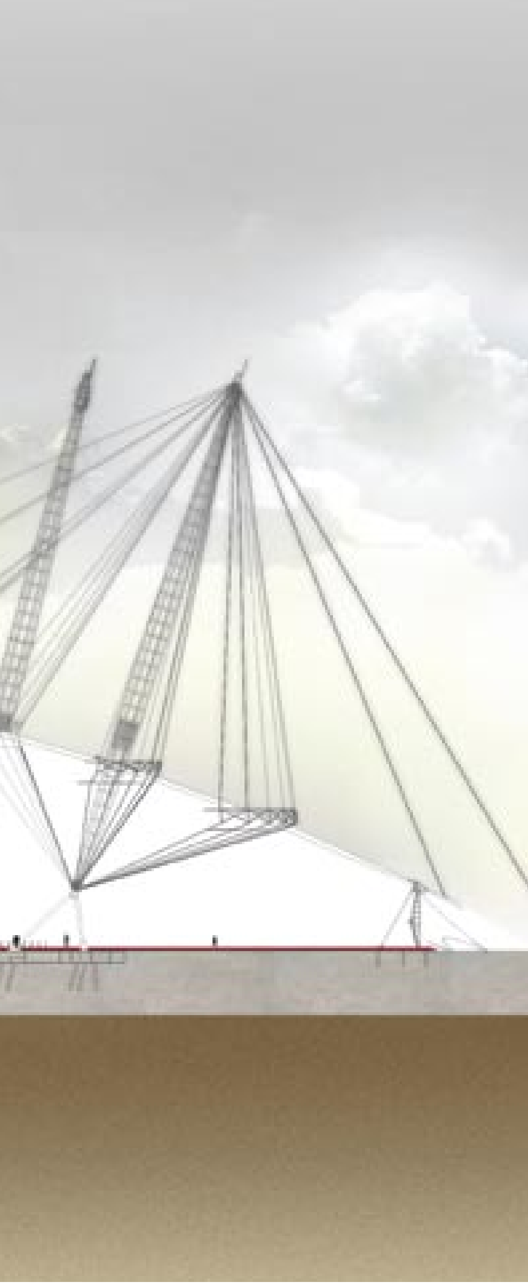
The spherical surface of O_2 Arena's roof has a radius of 1,145 ft and is exactly parallel to the surface of the dome canopy above. (The project's structural engineer, Buro Happold, also designed the original award-winning cable-net structure of the Millennium Dome itself, now called The O_2.) The structure comprises intersecting planar trusses of depths varying between 13 ft and 36 ft. The radial trusses cantilever by up to 72 ft beyond perimeter trusses that form a ring inside the roof support bearings and cores. The slender roof edge is dressed with a smooth "bullnose" cladding detail that undulates and seemingly floats in space over the upper concourse.

Buro Happold created a three-dimensional structural model of the project using Microstation, and Structural design analysis was carried out using STAAD.Pro. The ductwork and catwalk systems were fully integrated and coordinated into the design from the outset. The fabricator, Watsons Steel, then progressed with the steelwork production drawings using the 3D model as a starting point. During the initial stages of connection design, Watsons seconded an engineer to work in the Buro Happold offices, which aided the full understanding of the critical joint issues from the project's early stages.

The Roof

Constructing a building within a building created many challenges. For starters, the seating bowl design limited the space available for the new roof construction beneath the existing dome canopy; a minimum 16.5 ft of clearance between the new arena roof and the existing structure was required for building environment and smoke management considerations. The use of standard cranes was clearly not an option because of the proximity of the existing dome structure.

The whole roof was built at ground level, including all catwalks, services containment, ductwork, gondola winch platform, perimeter bullnose, gutters, fall-arrest systems, and acoustic cladding. It was built on



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a series of temporary trestles and then lifted by the strand-jacking method in a virtually completed condition. Working at this low vertical level maximized access and speed of construction and also improved safety.

Roof support was accomplished using only eight bearing points; the roof "floats" above the upper seating bowl and upper circulation concourse. It was lifted by strand jacks acting on the eight permanent support bearing points. The contractor chose to lift the roof in one piece, although the original concept allowed for raising it in several discrete, independently stable pieces, thereby enabling the progressive construction of the building frame below.

Each of the concrete cores at the eight points was designed so that the roof "slotted" into a gap in the core, allowing the roof to be lifted from directly above the bearing point. In two of the cores, several sections of floor slab were eliminated so that the roof steel could move vertically up past the floor edges. These were added at a later date. At four of the cores, quadruped support frames fitted into a free gap. They were hung from the end of the primary truss nodes as a means of lifting them to the top of the cores. Once the roof was positioned at the correct level, the quadrupeds were rotated and dropped onto the top of the core to support the roof.

The Lift Operation

Temporary steel lifting frames, with strand-climbing jacks, were positioned at the head of each core and used to lift the roof. All the jacks were controlled from a central computer, enabling them to be operated individually or simultaneously. Due to a lack of space above the temporary lifting frames, climbing jacks, rather than top-mounted jacks, were used.

Buro Happold worked closely with Watsons Steel and specialist lifter PSC Fagioli on the design of the lifting frames, the lift sequences, monitoring, and method statements. Some of the concrete cores were slender, with tall temporary steel frames mounted on them. Detailed non-linear buckling analysis of the combined roof, lifting frame, and core assemblies was carried out, together with independent checks on the design of the frames themselves, using the analysis results. Developments to the design of the lifting frames were made to ensure a rigorously checked and safe overall build sequence.

Lifting the roof safely required tight dimensional control and monitoring during the operation. The strands needed to remain within only 1 in. of vertical in order to avoid excessive lateral loads to the lifting frames, especially as the strands shortened at the top of the lift. In addition, the roof needed to remain almost perfectly horizontal, within a band of 1.2 in., so that the trusses and connections were not overstressed by a temporary condition in the process.

The lift operation was split into two stages—an 36-ft lift and a 52-ft lift—giving a total roof elevation of 88 ft. Each stage took three night shifts to complete, allowing other construction work to continue throughout the day. Particular care was taken on "lift-off" when the temporary frames rapidly picked up their full load and the roof swung free. During this step, a swing of only 0.40 in. to the north was experienced, which was testament to the accuracy of the construction, positioning, and robustness of the temporary lifting frames. In the three weeks between the two lift operations, the strand jacks were locked off and packs inserted as a precaution to control any tendency toward lateral movement. The roof hung on its strands while work continued to complete the final cladding envelope work, such as movement joint in-fill sections.

The lift progress was hampered by the need to constantly correct for level after every few jack strokes, in order to remain within the required tolerances. Problems with survey monitoring points and survey equipment were encountered periodically, but were overcome. Maintaining a balanced force within a pair of jacks at a single suspension point caused consternation at times. To combat this, movements were surveyed, plotted, and monitored for all core lift points (using survey targets mounted near the top and bottom position of the strands), as well as for some of the slender concrete cores. An automated surveying system was used so that measurements could be taken regularly, allowing the lift to proceed as quickly as possible.

Building the temporary lifting frames was a feat in and of itself, involving smaller jacking processes to push the 12-ton lift beams to within 5 ft of the underside of the existing cable net.

Design Features

As predicted and expected, large vertical structural deflections occurred at the time of lift-off from the ground level trestles. This formed an important and unique challenge for the structural design, one that is not often encountered in this way. To accommodate this movement, an extensive network of joints in the steelwork and cladding was incorporated. Steelwork joint movements were monitored before, dur-

By the Numbers

Arena roof steel: 2,800 tons
Main span: 421 ft
Approx. roof area: 186,000 sq. ft
Seating capacity: 22,000
Primary truss depth: 36 ft (max.)
Primary truss chord: 30-in.-diameter by 2.2-in.-thick tubes
Building height: 154 ft
Roof lift weight: 4,400 tons

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Above: The roof structure was built at ground level on a series of temporary trestles.

Below: The roof structure in its final postion.

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The end result is the O_2 Arena, Europe's most acoustically advanced concert venue.

ing, and after the initial lift, and this work showed the structure to have behaved as planned, with joints opening or closing by the predicted amount.

The catwalks and network of rigging beams at the level of the truss bottom chords are configured to support the complex sports lighting requirements and concert rigging demands. A maximum rigging load of 110 tons plus 22 tons of center-hung scoreboard can be suspended in the roof. In addition, the roof is "future-proofed" for possible external conditions, such as wind and snow, in the event that the dome canopy is removed.

The scoreboard can be fully retracted into the roof volume using the winch platform at the center of the roof to make way for in-the-round event configurations. Buro Happold continues to work with and advise the client on specific concert rigging requirements.

Roof Cladding

The cladding is tuned for optimum acoustic performance for break-out, break-in, and reverberation time. It is designed to be the most acoustically advanced venue in Europe. The cladding is also used as a "stressed skin" structure, in order to economize on the steel weight in the purlin members.

Cladding build-up options were tested against prescribed acoustic performance requirements, and the resulting deck weighs a hefty 14 psf, including an 8-in.-deep steel profile decking with acoustic absorption panels fixed to the soffit of each trough.

A large (approximately 52 ft by 46 ft) cladding and purlin trial panel was built, which proved to be extremely useful for many reasons:

- ✓ To check buildability of warped cladding fixed to spherical-faceted purlins
- ✓ As a physical fit-up test for complex purlin-to-truss steelwork bracket connections (also a function of spherical geometry)
- ✓ As an aid to test options for the cladding movement joints and edge support trim
- ✓ To develop and hone a safe method of cladding installation
- ✓ To force coordination and collaboration between all parties in advance of the main fast-track build (cladding contractor, steelwork contractor, main contractor, cladding designer, acoustics engineer, structural engineer, and procurement parties)
- ✓ To "de-risk" the construction process (faster, safer, etc.)

The panel, although large, is certain to have paid for itself many times over in terms of improved overall project performance and product quality.

Tight Space, Tight Schedule

All told, the O_2 Arena is a stunning venue with a special and unique design. The construction and lifting of the roof by controlled strand jacking of the whole 4,400-ton assembly was skillfully and safely achieved to a tight schedule, despite the challenges of construction within an existing building. MSC

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