

A BRITE INNOVATION CASE STUDY

Post-tensioned Steel Trusses for Long Span Roofs

Large, unobstructed clear spans were achieved by a post-tensioned steel solution in the Telstra Stadium roof reconfiguration. The solution reduced the cost of the roof and minimised loss of seat revenue during the construction period, compared to business-as-usual.

SELECTED PROJECT PARTICIPANTS

Client	Stadium Australia Trust
Head Contractor	Multiplex Constructions
Structural Designer (Roof)	Murray Ellen formerly of Bigspace Technologies Pty Ltd, now at s2 Corporation
Builder and Truss Fabricator	Ahrens Construction
Consulting Engineer	Sinclair Knight Merz
Architects	HOK Sport+Venue+ Event joint venture with Bligh Lobb Sports Architecture
Detail Engineer	SW Healey and Associates
Coatings Supplier	Ameron Coatings

This report is based on interviews with: Telstra Stadium, Murray Ellen and Ahrens Construction.



THE PROJECT

Telstra Stadium (formerly Stadium Australia) was reconfigured in 2003 to remove the temporary seating in the north and south terraces, which had been used for the 2000 Olympic Games and Paralympic Games. Two new 3,500m² roofs for all-weather accommodation were constructed over the stadium ends. The seating stands on the East and West sides of the playing field were placed on moving frames so that the arena could be quickly adjusted for rectangular and oval settings.

The reconfiguration cost \$80 million, with the roofing component being around \$10 million, and was completed without disruption to the scheduled events at the stadium. The post-tensioned system for the roof was adopted to overcome difficulties that a business-as-usual design was likely to cause.

THE ACHIEVEMENT

The construction system for the new roofs allowed the project to be completed on time and budget, keeping loss of seat revenue during construction to a minimum.

The project was completed in time for the 2003 Rugby World Cup, despite a tight timeline for design and construction. The truss members were prefabricated and assembled on the ground outside the stadium, so the concourse around the ground was relatively unobstructed on match days. The two main trusses were erected in a single week, within a six month construction program that saw no serious injuries to workers. The end result is what is believed to be a world-first post-tensioned steel roof for a sporting stadium.

The project was awarded the 2004 ASI Structural Engineering Steel Design Award for NSW and the ACT.

THE INNOVATION

A post-tensioned roof was adopted to avoid problems that were likely to be encountered with a more conventional steel roof. A more conventional roof was likely to require every connection node to be propped until the roof was completed. A forest of large props was likely to block sightlines, reducing the seating capacity by roughly 9,000 seats at each end of the stadium during construction. Cranes were likely to have been stationed on the arena, killing off significant areas of turf. A post-tensioned roof avoided these potential problems.

The principles of post-tensioning have long been understood by structural designers,

but they have not often been applied to steel frame structures. The behaviour of a structure can be predicted by applying loads to a theoretical "string line" – compression domes have been designed this way for centuries. Traditionally, loads simulating the self weight of the dome were hung from a string. The shape taken up by the string was plotted and inverted to form the design of the dome. The tension in the string line was measured and this determined the thickness of the dome structure.

A similar process was used for the stadium roof, using 3D computer modelling instead of the physical string line. In this case, the string line shape was not inverted but accepted as the form of the main catenary trusses. There was no need for inversion because the tension and compression properties of steel are strong enough to support the load (unlike a masonry dome, which has very little tensile strength).

The string line approach does not, however, deal with deflection, so sophisticated software was used to model the loads in the members and deflections in the structure. The string line is represented by the post-tensioned cables in the truss bottom chords. These cables are loaded by hydraulic stressing to resist the external forces acting on the structure.

All the prefabricated members which make up the trusses are straight lines or simple curves so that, while a very large truss is produced, the components are easily transported and lifted into place. Once assembled, the truss was in effect proof-tested by the stressing process. The approximately six kilometres of stressing cables in the bottom chords of the trusses were stressed by hydraulic jacks then fixed in place with high strength grout once they were in position.

The connecting joints for the post-tensioned roof structure are all simple "butterfly", "half moon" and "end plate" connections, so the truss sections can be quickly and easily bolted together on site. The trusses were assembled in two relatively small areas on the concourse outside the stadium. A 400 tonne and an 800 tonne crane on the concourse were used in tandem to lift the main trusses into place. Smaller cranes with long reach capacity completed the assembly, also



from outside the stadium. This included the secondary trusses and the 10m x 10m framed polycarbonate panels that finished the roof.

The stored energy in the stressed cables reduces deflection under load. This allowed the main trusses to span the 114 metres between the existing roofs without any intermediate support or propping during construction, leaving the seating under the roofs available for scheduled events.

THE BENEFITS

The main benefits of the post-tensioned roof design and lean construction methods at Telstra Stadium can be compared to a more conventional steel roof design and construction methodology. Estimated reductions include:

- 50% in the weight of steelwork needed to span the roof opening, and associated transport costs;
- \$3 million to fabricate and erect the structural steel;
- 25% in erection time; and
- 40% in production time for the steel fabricator.

From the point of view of the stadium management, the chief benefit was that loss of seat revenue during the 2003 NRL, AFL and Rugby Union football season was minimised to the greatest extent possible. More conventional approaches would have required some seating areas to be fenced off for at least six months, as has been seen at some other major sporting venues. The revenue gained from approximately 18,000 seats that were kept available over the six month construction period is estimated to be \$2.7 million.

The sporting public had the benefit of continued use of the stadium during the roof reconfiguration period without any obstruction to sightlines in any of the stadium seating. People had continued access to most of the public areas around the stadium during construction. This maintained an important recreational resource for the city of Sydney.

The roof has been compared to the shape of the brim of an "Akubra" hat and is widely accepted as an aesthetically pleasing solution to a difficult geometric problem. The client gave high importance

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to the new roof looking like a natural extension of the existing roof, and this is thought to have been achieved.

THE IMPLEMENTATION PROCESS

Tight timelines and the need to keep the stadium operating were the key factors driving the use of innovative technology for the Telstra Stadium roof reconfiguration. The Structural Designer submitted his solution to the design team as an economic way of achieving the stadium roof before the deadline of the World Cup. The booming construction industry meant that it was difficult to find a local steel fabricator to do the work at short notice. However, the relatively small size of the prefabricated components meant that they could be produced in Adelaide and shipped to Sydney at a competitive price. Managing the supply chain in this way, in response to market conditions, helped to minimise project costs.

Indeed, risk management is a critical issue in implementing "cutting edge" technology. The Structural Designer on Telstra Stadium chose to manage the stressing of the cables himself. Effectively, he acted as a hybrid between a specialist sub-contractor and a consulting engineer. Contractual arrangements were tailored to suit this dual role, which is unusual in the construction industry. The Structural Designer also requires intellectual property payments for the use of his system, a practice which is rare among construction contractors, though increasingly accepted by industry clients, particularly those who understand the value of intellectual property.

The Structural Designer sought to maximise the advantages of his solution and reduce the risk. He maintains an active research and development program, despite heading a small firm with only six employees. In order to leverage his efforts, he develops associations with university research bodies who test and validate his processes.

OVERCOMING DIFFICULTIES

The redesign of the roof structure meant that the builder and truss fabricator had considerable work to strengthen the four existing support points, which now carry the load of the new roofs. This was com-



plex and difficult work that had to be performed from underslung scaffolding. The effectiveness of this work was underpinned by good relationships between project team members.

Prefabrication of the structural members required very careful measurement of the opening between the existing roof structures. Steel expands and contracts as the temperature changes, so the size of the opening varies, and this had to be catered for in the fixing system. Advanced 3D laser technology was supplied by the consulting engineer to survey the existing structure. Stickers were placed on the structure and several measurements taken to determine the average dimension of the span. The main span expanded by 18mm in the course of one day. The main trusses were set in place at 1pm when the temperature reached 26° Celsius, which was the mean temperature for the arches. There was no opportunity to alter the trusses once they were in place, so it was essential to accurately measure the dimensions and tolerances for the joints.

All the workshop drawings for the steelwork were recorded in 3D CAD, as were all the fieldwork measurements. These two data sets were correlated in the CAD system. The task would have been almost impossible as little as 10 years ago, without the 3D modelling for the complex geometrical shapes.



The assembly and erection of the framing involved several scheduled stages. Priority was given to maintaining the stadium's program of five major events during construction and this restricted operations significantly. Good relationships underpinned coordination of all the players involved, and direct chains of responsibility for the work were essential to its successful completion.

LESSONS LEARNED

- Innovative structural technologies require close attention to quality control and careful installation practices, to manage risk.
- When the expertise to successfully implement a technology is highly specialised, the specialist needs to closely supervise the installation.
- Putting a fair value on the intellectual property in a construction innovation can mean developing systems of remuneration that are quite different from the standard contractor to sub-contractor fee structure.
- 3D modelling technologies allow the fabrication of complex geometrical forms that would otherwise be impractical.
- Complex shapes and new technologies often require a fresh approach to calculating and validating structural systems.
- In-house research and development can be effectively supplemented through relationships with universities and other research bodies.
- Market conditions can drive supply-chain innovation.
- The nature of a client's business, particularly on brownfield sites, can put constraints on a project, thus sponsoring innovation.

For Further Information
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