Cable Stayed Grandstand Roofs for the 2000 Olympics

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1. INTRODUCTION

Connell Wagner has had recent involvement in two projects with cable stayed roofs. The first was the Sydney International Athletic Centre, completed in 1992. It included a cable stay arrangement supporting the outer edge of the grandstand roof. Essentially, a two-dimensional cable-stay and catenary system restrained the outer edge movements against downward and upward loads. The more recent project is the State Hockey Centre.

The State Hockey Centre is the venue for hockey for the 2000 Olympics in Sydney. The roof for the 1500 seat grandstand is held up by cables suspended from a single rear mast, and held down by catenaries spanning 70 meters end to end. These catenaries are curved in opposite directions in plan, providing lateral stability. The roof soars completely clear of the grandstand, and consequently the grandstand structure is not penalised for its support of the roof. This is an extremely light and very unusual roof. The authors are not aware of any other similar scheme elsewhere in the world. The project was completed in August 1998.

The evolution of design on these projects will be discussed in this paper.

2. SYDNEY INTERNATIONAL ATHLETIC CENTRE

2.1 GENERAL

The Sydney International Athletic Centre includes a competition arena and a warm-up track, and is capable of functioning as the venue for a wide range of national and international events. The competition arena will be used as the warm-up track for the 2000 Olympics. The grandstand for the competition arena seats 5,000 people over half of whom are under cover of a unique roof structure.

2.2 ALTERNATIVES FOR ROOF STRUCTURE

The roof of the grandstand was the subject of a very intensive study of many and varied alternatives. At the beginning, a method of evaluation was devised to cope with all the options input, which included relevant data of cost, buildability, and architectural influences such as image, environmental impact and planning considerations.

Two basic roof structure forms are possible for this roof: (a) cantilever from the rear of the stand; (b) clear span structure. Cantilever structures have certainly been the most common structural form for stadia of this type. However, as the cantilever span increases, the cost of the structure increases disproportionately.

An alternative solution is to provide a structure, which spans over the roof from end to end. This could take the form of a large arch, a large truss, or a cable suspension system. The advantages of this are that the stand structure and all of its connections are not penalised by the need to resist the cantilever action of the roof, and the roof beams comprise a simple spanning structure with the ability to optimise the location of the supporting cable truss.

In the analysis of alternatives, these matters were studied in detail and structural schemes were prepared and analysed for economy, for various alternatives of the above two basic forms. Options included: large truss structure spanning the entire length of the stand; cantilever truss schemes; cantilever girders; cantilever space frame; fabric roof; cable suspended roof (chosen scheme).

The decision making matrix showed that of all the alternatives considered, the cable suspended roof was the most desirable and marginally more economical than other options. The ability to attach the floodlights to the masts required to support the cables contributed dramatically to the economy of this scheme, as effectively two major lighting structures were able to be deleted.

The cable roof structure (Fig. 1) is remarkably lightweight and inherently efficient as it utilises tension to transfer all vertical loads from both dead load and wind load. The chosen structure also more readily permits the desired roof shape, which angles toward the front and is curved in plan. This shape enables the desired number and location of people to be placed under cover with less roof area than other more conventional profiles.

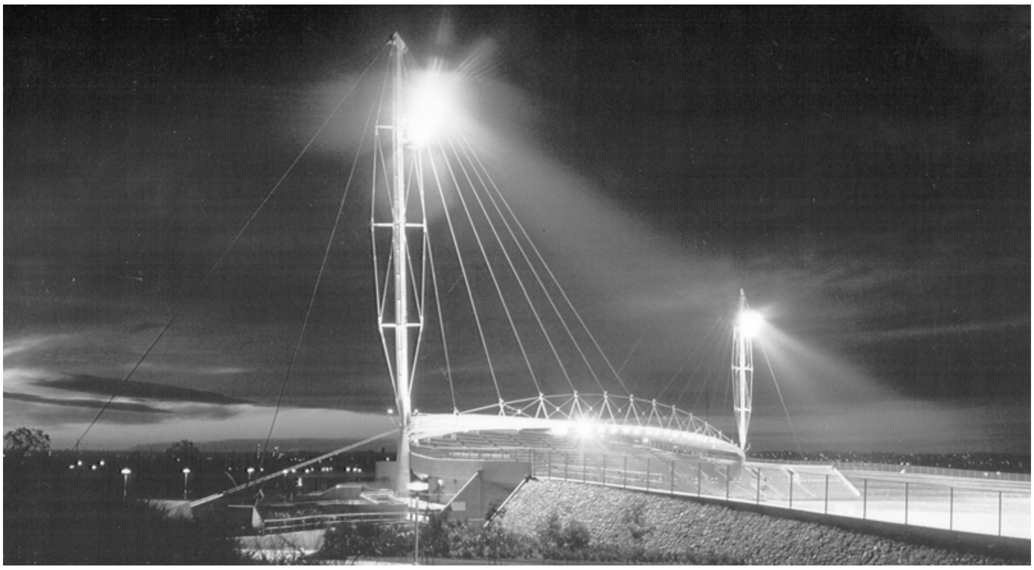


Figure 1. Cable-Stayed Roof of Sydney International Athletic Centre

2.3 THE ADOPTED STRUCTURAL SCHEME

The cable suspended roof structure can be fairly simply described as follows: Two 45m high masts, approximately 150m apart, provide the support for the front of the roof (Fig. 1). Six inclined forestays, ranging between 35mm to 60mm diameter, transfer the downward load from the rafters on either half of the roof to the adjacent mast (Fig. 2). Two backstays, 85mm in diameter, anchor the mast to the ground.

A pair of 63mm diameter catenary cables are taken through the whole roof span and over the top of the mast pedestals. They are then anchored to the ground on either side providing resistance to wind uplift. The use of a pair of cables for the catenary provides a degree of redundancy to one of the most critical elements in the cable support system. The catenary cables are raised above the roof profile for greater curvature, and then connected to and pre-tensioned against the forestays. This pretension system serves two purposes: (a) stiffening the catenary cables; (b) minimising sag of forestays under self-weight.

All cables are constructed from galvanised high-tensile wires, 7mm in diameter and with a parallel configuration.

Box section steel rafters at approximately 11.8m spacing support conventional purlins and metal deck roofing. The rafters are hung by droppers from the catenary cable at the front of the roof and are supported on steel columns at the rear (Fig. 2). Purlins supporting metal deck roofing and ceiling sheeting span between the rafters.

A cable truss is also formed by a longitudinal compression tie at the roof level, linked by vertical cross bracing to the catenary cable and connected to the masts pedestal. This provides additional stiffness to the roof, which is particularly beneficial for controlling deflections under non-uniform wind loads.

The masts were also the subjects of a study of alternative structures, from single tubes to multiple tubes to cable braced forms. The chosen profile, a cable braced multiple tube, is both economical and most desirable architecturally (Fig. 3).

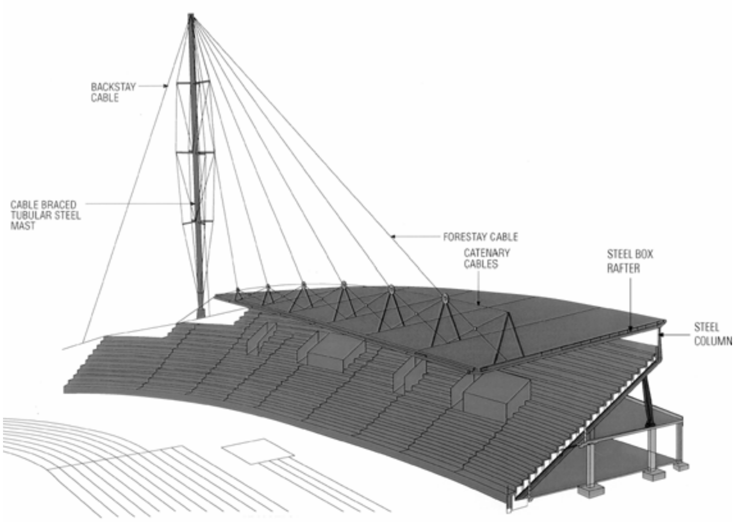


Figure 2. Structural Components of the Roof

Figure 3. Cable-Stayed Multiple-Tube Mast

2.4 FORM-FINDING AND OTHER TECHNICAL CONSIDERATIONS

The stiffness of a cable-stayed structure is largely determined by detailed considerations of its geometry and the cable pre-tensions. The most efficient geometry is one where all the members receive an optimum level of pretension, which provides sufficient stiffness to all members without overloading them. The geometry of the cable system of the athletic centre was optimised through a "form-finding" exercise. The vertical distances between the catenary-forestay connections and the roof profile were used as geometrical variables in this exercise.

The size of catenary and backstay cables was dictated by strength requirements, while forestay sizes were governed by serviceability considerations, i.e., the level of prestress required to control deflections. Cable pretensions were set to ensure that, under a one year return period wind, the sag at the mid-span of the forestays was not greater than the cable length divided by 250. This was based on visual considerations.

3. STATE HOCKEY CENTRE

3.1 GENERAL

The new State Hockey Centre is located on the site of the existing State Hockey Centre at Homebush Bay, Sydney, and will function as the main competition venue for the 2000 Olympic Games. It includes a grandstand, seating over 1,500 spectators and officials under a spectacular pavilion-style roof. Connell Wagner has developed a dramatic lightweight roof structure, which responds to the client's request for a state-of-the-art facility portraying a distinctive image and identity for the sport of Hockey in Sydney for the 2000 Olympics and beyond.

3.2 THE ROOF STRUCTURE

Connell Wagner suggested several conventional and semi-conventional solutions for the roof in line with the Master plan, and to complement the adjacent State Sports Centre. However, the one which seemed to best address the architect's vision of a pavilion was the concept of a cable-stayed roof suspended from a single mast at the rear of the structure (Fig. 4). An important benefit of this structural form is that it soars above the grandstand below, making it visually spectacular. It also avoids imposing any roof loads on the grandstand.

Figure 4. Grandstand Roof of Hockey Centre

The roof is lens shaped in plan and consists of five facets from the surface of a cylinder. It spans 70m from end to end with a maximum height of 9m at the centre. Steel was selected for the supporting members with steel roof sheeting. Six rafters are positioned at approximately 12m centres defining the borders of the five facets of the roof (Fig. 4). The rafters on the side edges of the roof are 406mm CHS members, while the four intermediate ones are 400mm deep, 300mm wide box sections tapering to a 200mm depth over a 4m length at either end.

A total of 12 forestay cables, 35mm and 45mm in diameter, are suspended from the rear 40m tall mast. They are connected to the rafters at the rear edge and at the two-third position from the rear, hence supporting the self-weight and downward imposed loading of the roof (Fig. 5). The mast is a fabricated steel tube with a maximum diameter of 800mm, tapering to 400mm over a 5m length at either end (Fig. 6). Two backstays, each measuring 100mm in diameter, stabilise the mast. Figure 7 depicts the downward load-resisting system for the roof.

Figure 5. Stays Merging to Mast Head

Figure 6. Mast Tied by Backstays

Two primary catenaries run along the rear edge and the two-third position of the roof, linking the forestay-rafter connection nodes (Fig. 8). They are connected to and stressed against the forestay cables, providing the main strength and stiffness against uplift wind loads. A third, essentially non-prestressed catenary is also positioned along the front edge of the roof providing additional strength and stiffness to the roof under wind uplift. The front two (prestressed and non-prestressed) catenaries also resist loads tending to push the roof towards the hockey pitch, while the rear catenary resists the loads pushing the roof away from the hockey pitch. The uplift and lateral load resisting components are highlighted in Figure 8.

Within the roof plane, the three catenaries are made of segments of 324mm CHS members. Beyond the side edges of the roof, however, the catenary actions are extended by three cables linking the ends of the steel tube catenaries to a focal point at the tip of a tied-down steel strut system. The strut system is fabricated in a shape similar to a wishbone, whose 10m long legs are tapered cruciform sections with maximum dimension of 600mm (Fig. 9). A single 95mm tie-down cable anchors the strut system back to the ground, hence completing the catenary actions (Fig. 10).

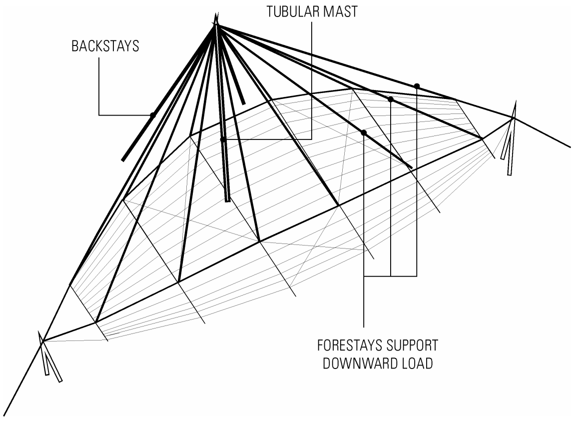


Figure 7. Downward Load Resisting System

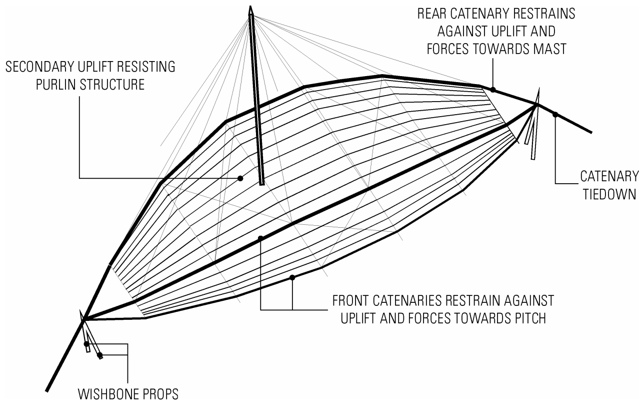


Figure 8. Uplift Load Resisting System

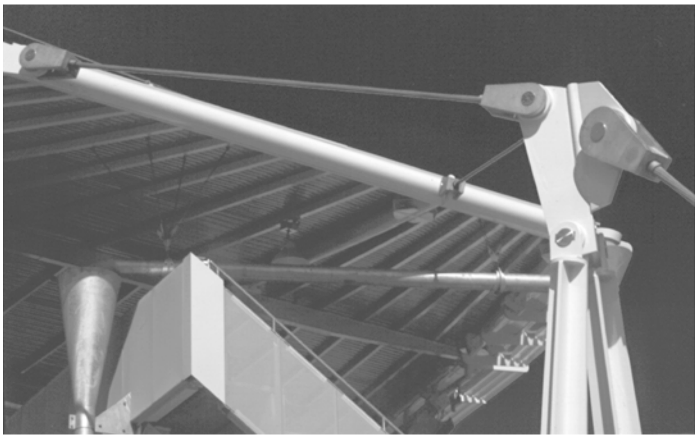


Figure 9. Wishbone Top and Link Cables

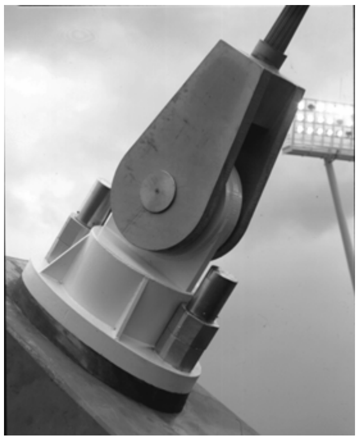


Figure 10. Tie-down Base

To further refine the concept of converging catenaries, axial capacities of the purlins were also used as supplementary catenaries for additional strength and stiffness (Fig 8). This innovative solution substantially reduced the required pretension without penalising the design of the purlins, and hence, led to a significant economical benefit associated with reduced sizes for cables and foundations.

3.3 RESOLUTION OF FORM AND GEOMETRY

A critical decision which Connell Wagner faced was whether to make the roof a true cylinder with a curved form, or to make it a series of straight facets approximating the surface of the cylinder. Pivotal to this decision were the various functions of the purlins and the significance of the purlins acting as catenaries. This meant that they tended to converge at either end, pointing at the top of the wishbone-shaped anchor. The form took on the shape of an upside-down hammock with the purlins as elliptical strands traced around the surface of the cylinder (Fig. 4). The end rafters (Fig. 9) were conceived as rigid straining bars, transferring the loads to the cables linking the roof to the buttresses.

The type of member for the purlins became an important issue to maintain simplicity and contain costs. Open sections were rejected because they would provide places for birds to sit. Cold formed sections were rejected because they would clearly be inappropriate for transmitting the axial forces. CHS purlins would have achieved the true elliptical geometry but would have been less efficient bending members than RHS members.

Using the elliptical geometry would have required that every purlin be different over each half of the structure. RHS purlins could not be curved to the elliptical shape required. In assessing the advantages and disadvantages, simplicity and cost prevailed. RHS purlins were chosen with the roof approximated as a series of five straight sections, each approximately 12 metres long.

Eliminating the bracing in the roof (as desired by the architect) substantially influenced the size of the main catenary members. Without bracing, the catenaries would have been required to prevent racking in the plane of the roof. The catenaries and rafters would have acted as a Vierendeel truss in this plane. The optimum solution was a minimalist bracing in only three of the 10 bays, which avoided penalising the catenaries and added some Vierendeel action.

The global geometry of the roof was most efficient when the primary load-resisting system resisted loads axially, and where all the primary elements could be sufficiently stressed to provide adequate stiffness without overstressing any of the elements. For the roof of the Hockey Centre, the primary structure consists of two main catenary systems plus rafters, forestays, mast and backstays. When the primary structure is considered as having axial capacity only, the structure is once redundant, or statistically determinate for prestressing. This means that for any given geometry of members there is a set of pretension forces, which can be factored up or down.

In order to optimise the geometry a form-finding exercise was performed. The key objective was to minimise racking deformations in the plane of the roof under the combined self-weight and prestress loading condition. Variables such as the position of the front prestressed catenary, the wishbone geometry, and the orientation of tie-down cables were used in this form-finding exercise. With the roof as a series of straight facets, adjustment to these variables was easily achieved without complicating the setout.

A feature of this roof structure was its complete reliance on its pretension (or geometric stiffness) to resist asymmetric upward and downward loads. This added another dimension to the issue of optimum geometry and required level of prestress as discussed earlier for the Athletic Centre.

3.4 STRUCTURAL DYNAMICS AND WIND ENGINEERING

With its symmetric catenary systems, the roof structure is inherently more flexible in its asymmetric mode than the symmetric mode. Our three-dimensional dynamic analyses of the roof structure indicated that the asymmetric stiffness is very sensitive to the level of prestressing. The geometric stiffness generated by the prestressing increased the asymmetric stiffness and natural frequency of the roof tremendously. Using a conservative (lower-bound) level of prestressing, the fundamental vibrational modes of the structure were found to be in the following order:

- Anti-symmetric vertical (rocking) mode with a natural frequency of 0.87 Hz.
- Symmetric vertical (double-curvature) mode with a natural frequency of 1.12 Hz.
- Anti-symmetric torsional mode with a natural frequency of 1.32 Hz.

The natural frequencies are relatively low and closely spaced. Strong modal interactions can therefore be expected during dynamic excitation. Considering this and the potential wind-sensitivity of this unusual structural form, it was decided to conduct wind tunnel testing on a scaled aero-elastic model of the structure (Fig. 11).

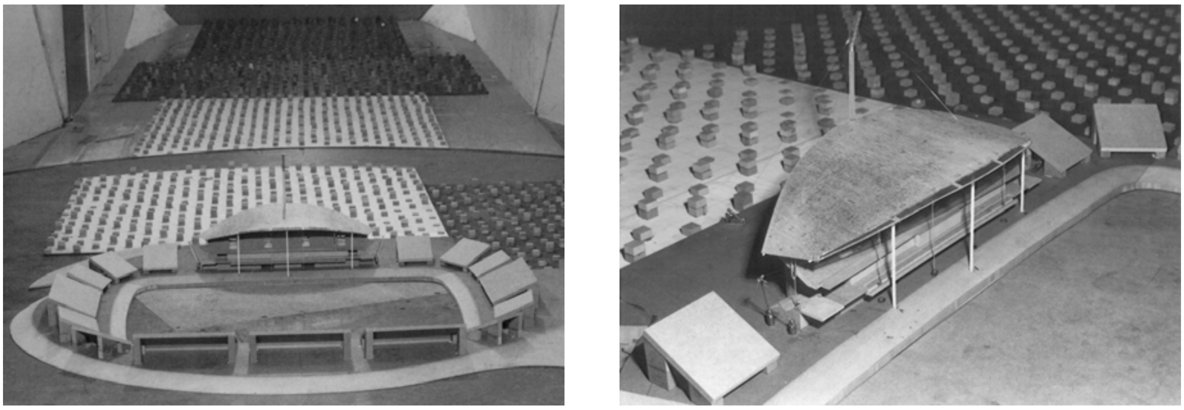


Figure 11. Wind Tunnel Test Model for Hockey Centre

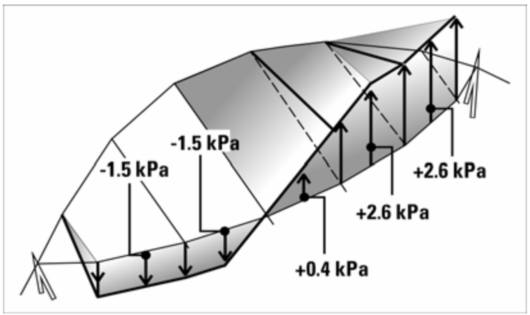
The aero-elastic model included the grandstand structures and its surroundings, and was tested in the boundary layer wind tunnel facility of Monash University under the supervision of Professor Bill Melbourne. Measurements were made for a 360° range of wind directions. The results indicated that the structure would be dynamically stable, and produced the ultimate design wind load cases shown in Figure 12.

The critical load case for structural design of most elements was found to be the asymmetric load case. This structure is very stiff under uniform or near uniform upward or downward forces.

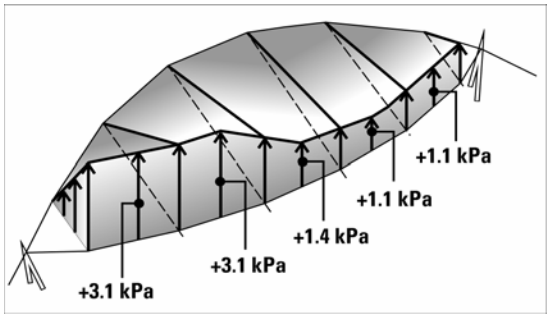
3.5 DETAILED ANALYSIS AND TESTING

In order to correctly evaluate the response of this highly nonlinear structure to the loading conditions, Connell Wagner conducted detailed 3D nonlinear analyses using Microstran suite of programs. These analyses included many advanced features. The analyses were based on full large displacement formulations, where tension stiffening and other secondary effects (including P-Δ and P-δ effects) were correctly accounted for. Furthermore, catenary cable elements were employed to model the sag effects in the forestays and the backstays.

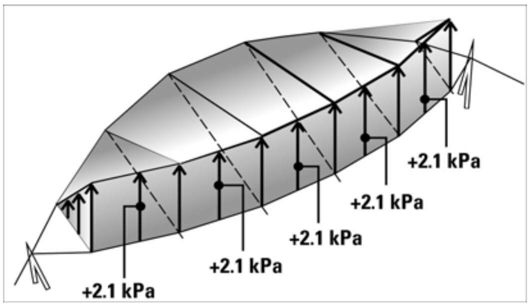
The analyses showed that with the minimal in-plane bracings provided, roof panels required to endure significant racking deformations under asymmetric loading. This could cause the roof sheeting distress, even tearing its fixings to the support structure. In consultation with the suppliers, BHP, Connell Wagner devised a test to assess the resistance of the sheet to racking and it was found to perform adequately under deformations. Connell Wagner's experience on this project, and subsequent production of data for sheeting, will assist other projects with more severe applications than were previously considered possible.



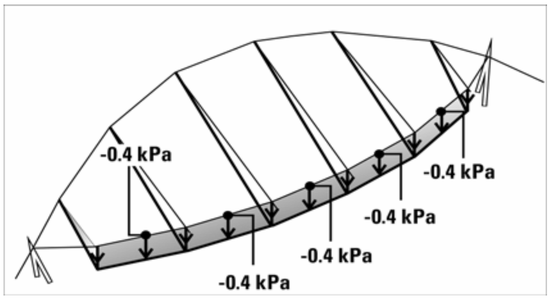
(a) Asymmetric Up and Down Wind



(b) Skew Uplift



(c) Uniform Uplift



(d) Uniform Down Wind

Figure 12. Ultimate Design Wind Load Cases

When the roof moves under load, there is a change in the angle of the intersection between the cables and their connection cleats. To accommodate these rotations without distressing the cleat or the cable ends, Connell Wagner incorporated off-the-shelf spherical bearings into the cable end connection details. This application of bearings in a cable-supported structure is quite unusual.

3.6 CONSTRUCTION

The roof was constructed on a temporary support structure and the cables were then installed and stressed. These sequences involved several important aspects:

- It was necessary to get the stress into the primary structure to maximise its effect. Stressing the purlins was not desirable, as it would dramatically increase the design load in those elements and the rafters. The purlins and rafters would then have transmitted the stress back to the cables.

- Conversely, if the roof were stressed without its dead weight in place it would move substantially when the dead weight was added.

To overcome these problems, the purlins and roof sheeting were erected prior to stressing. The purlins were left unbolted at one end and the sheeting was placed in bundles adjacent to the support. With the dead load in place, no unwanted load paths existed for the stressing.

4. CONCLUSIONS

Innovative approaches towards the design of the roofs of the Athletic and Hockey Centres led to the creation of two very unique cable-stayed roofs for the 2000 Olympics. Connell Wagner engineers successfully met many design challenges associated with optimising geometry, form and load resisting system. This involved developing project-specific design rules for the cable structures, and a thorough understanding of the form-finding process and the significance of geometric stiffness and pretensions.

The roof structure of the Hockey Centre is considerably more challenging given the total and three-dimensional nature of the cable support. The innovative engineering approach employed, however, created a remarkably lightweight roof structure. With a weight of 57 kg/m^2, it compares most favourably with the more conventional roof on the Great Southern Stand of the Melbourne Cricket Ground, which weighs 85 kg/m^2. The complete separation of the roof from the grandstand offers elegance and economy, as well as interesting possibilities for roofing of existing open grandstands.

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