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# Centre Court Stadium Roof, Melbourne, Australia

Toiture du stade du court principal, Melbourne, Australie

Überdachung des Hauptspielplatz-Stadiums, Melbourne, Australien

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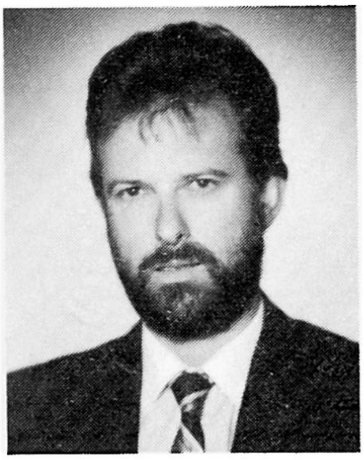

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**SUMMARY**
The centre court stadium of Australia's new National Tennis Centre seats 15,000 spectators and is required to double as a multi-function entertainment venue. For tennis use the stadium must be open, whilst for other uses it must be fully closed with an acoustically insulated roof. This paper describes the development and construction of the roof system, which comprises a cantilevered fixed roof and a unique retractable roof, which when retracted, leaves an opening 75 m x 60 m in the centre of the fixed roof.

**RÉSUMÉ**
Le stade du court principal du nouveau centre national australien de tennis dispose de 15000 places et doit doubler sa capacité lorsqu'il remplit sa fonction de centre de loisirs à buts multiples. D'une part le stade doit rester ouvert pour les joueurs de tennis, et d'autre part il doit être complètement couvert, avec un toit acoustiquement isolant pour les autres utilisateurs de ce centre. Ce document décrit le projet et la construction du système utilisé pour toiture, qui comprend un toit fixe à consoles et un unique toit ouvrant, qui lorsqu'il est ouvert, laisse une ouverture de 75 m x 60 m.

**ZUSAMMENFASSUNG**
Das Hauptspielplatz-Stadium des neuen nationalen Tenniszentrums ist mit Sitzplätzen für 15000 Zuschauer ausgestattet und dient mit doppelter Kapazität als ein multi-funktioneller Unterhaltungs-Treffpunkt. Für Tennisspiele muss das Stadium geöffnet sein, während es für die zweite Nutzung mit einem akustisch isolierten Dach völlig geschlossen sein muss. Dieser Beitrag beschreibt die Entwicklung und Konstruktion des Dach-Systems. Dieses besteht aus einem festen Ausleger-Dach und einem zurückziehbaren Dach, welches im eingezogenen Zustand eine Öffnung von 75 m x 60 m in der Mitte des festen Daches offen lässt.

# 1. INTRODUCTION

The National Tennis Centre provides world class tennis facilities aimed at maintaining the Australian Open Tennis Championships as one of the four Grand Slam events and for other major national and international tennis tournaments.

The facility includes the centre court stadium, which seats 15,000 spectators, plus two match court stadia seating 6,000 and 3,000 respectively, which are linked to the centre court stadium by a common concourse. Parking for 300 cars is provided beneath the two match courts and offices, player, umpire, ball staff, media and catering facilities are located beneath the centre court stadium. Thirteen outdoor and five indoor courts complete the centre.

The centre court stadium is also used as a multi-function entertainment venue for events such as rock concerts and circuses. The problem of providing for the different needs of an open air tennis stadium and a closed entertainment centre was solved by the development of an acoustically insulated roof covering the entire centre court stadium. The roof is in two sections: a fixed section covering the stadium seating; and a two-part retractable section covering the central area. When fully open the retractable roof halves are parked at the north and south ends of the stadium above the fixed roof, leaving an opening in the centre of the fixed roof 75m x 60m in size, oriented so as to minimise shadow effects on the court.

# 2. FIXED GRANDSTAND ROOF

## 2.1 Layout and Geometry

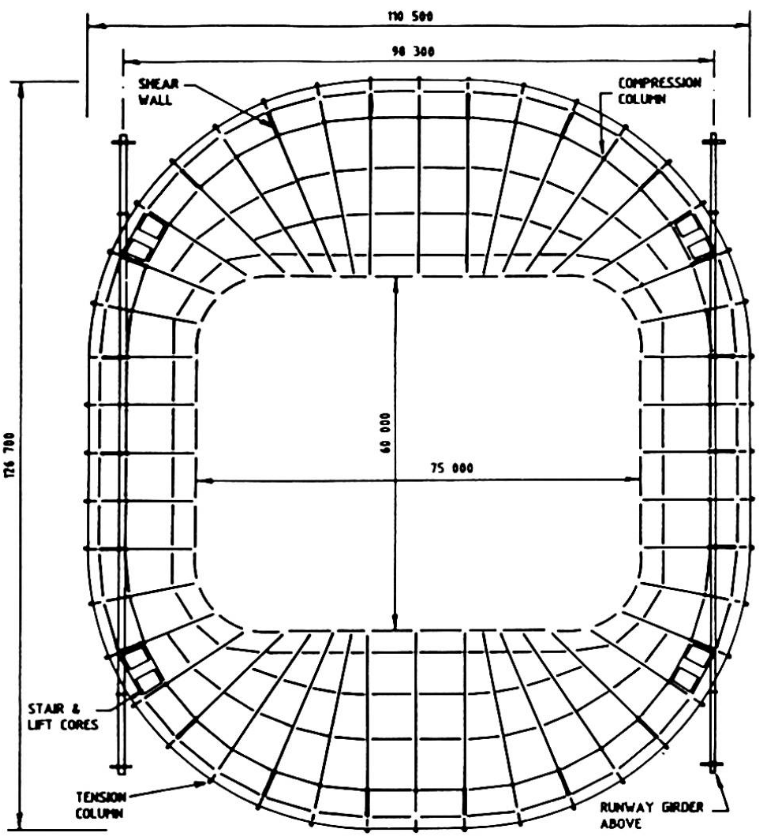


Fig. 1 Layout of Fixed Grandstand Roof

The fixed roof comprises 44 cantilevered radial trusses connected together by a series of circumferential trusses around the full perimeter of the stadium. Radial trusses vary in cantilever length from 11.35m along the East and West sides to 26.7m along the North and South sides, with a constant back span of 6.65m (Figure 1).

The geometry of the radial trusses was established by the requirement for all trusses to be at a constant level at three locations, these being the fascia around the roof opening, the fascia around the outside of the stadium and the roof line above the forward supporting column of the trusses. Because of the varying cantilever lengths this leads to radial trusses with varying grades from 1 in 40 (the minimum for drainage purposes) to 1 in 17 for the shorter cantilevers.

The radial trusses are supported vertically via the concrete raker beams which support the upper level seating. The front (compression) columns are located directly above the 600mm dia. concrete columns supporting the raker beams, whilst the rear (tension) columns are attached to the cantilever end of the raker beams. The tension column anchorage is adjustable to facilitate profile modifications during erection and at any stage during the life of the building. Radial trusses are connected to concrete shear walls located at every second raker beam to transfer horizontal loads to the substructure.

The radial trusses are supported upon 300mm diameter x 50mm elastomeric bearings at the front compression columns to accommodate thermal movements.

The radial trusses are connected together by 3 to 5 circumferential trusses at 8m centres maximum. These serve to brace the radial trusses, to distribute applied vertical loading and for the attachment of external perimeter fascia panels.

The total weight of structural steelwork in the fixed roof is 480 tonnes, excluding roof and ceiling purlins and catwalk grating.

## 2.2 Design

The fixed roof was analysed for static and dynamic vertical loading, thermal effects, wind pressures and support deformations. Taking advantage of symmetry effects, a single quadrant of the roof was modelled as a two dimensional grillage of horizontal beam elements with section properties specifically determined to simulate the deformation characteristics of the actual framework.

All cantilevered radial trusses were provided with spring supports to simulate the actual stiffnesses of the supports, and the separate effects of long term creep displacements at these supports were also included in the force envelopes for member design.

The determination of vertical wind loading for a roof containing a retractable section is complex and for this reason specialist assistance was sought to ascertain an appropriate upper bound pressure for design purposes. The critical case for uplift pressure occurs when the retractable roof is fully open and the wind approaches from the North or South across the stadium, striking the downwind cantilever. However, initial analyses proved that load cases incorporating wind effects were not the governing cases, so conservative wind pressures were adopted for design purposes to avoid the need for exhaustive model testing.

At the Southern end of the stadium the roof is designed to accommodate 35 tonnes of stage related entertainment equipment, such as speaker and lighting clusters. This loading is restricted to 1.1 tonnes at each of 32 specially provided hoisting points located at the nodal points of the radial trusses.

A separate study was made into the dynamic behaviour of the combined roof and concrete substructure to ascertain the susceptibility of the fixed roof to wind induced resonance and the response of the upper raker beams to spectator movements (particularly those of a rhythmic nature which might occur during, say, a pop concert).

The fundamental frequencies of vibration of the fixed roof were extracted from a three dimensional eigenvalue analysis of a full quadrant of the stadium.

The predicted response of the grandstand raker beams to rhythmic forces resulted in the addition of intermediate columns to the upper raker beams in order to maintain the potential resonant forces and accelerations in these beams to within acceptable limit states.

### 2.3 Fabrication and Erection

The steelwork of the fixed roof was shop assembled and welded into component lengths up to 20m long for transportation to site. Once on site components were erected by mobile crane, the maximum lift being 6.1 tonnes. All field connections were made with Grade 8.8 high strength structural bolts tensioned to act in a bearing mode. The roof was designed on the basis that propping of the radial trusses would be unnecessary. The radial trusses were precambered by amounts varying up to 180mm in order to allow for approximately 80% of the permanent theoretical dead load deflections.

Erection of the fixed roof followed erection of the retractable roof runway girders and commenced simultaneously at the East and West sides of the stadium and progressed towards the North and then the South ends of the stadium sequentially. Radial truss erection was followed immediately by the adjoining circumferential trusses in a predetermined order. Tensioning of bolts was left until the completion of all steelwork at each end of the stadium. The entire erection procedure was enhanced by the use of purpose-designed mobile working platforms covering the full area beneath two of the longest radial trusses. These platforms were adjustable vertically to provide access for the later installation of the ceiling.

## 3. RETRACTABLE ROOF AND RUNWAY

### 3.1 Layout and Geometry

The retractable roof comprises 2 separate sections, each consisting of an exposed framework spanning 98.3m and supporting a suspended roof system 75m x 30m, sufficient to cover half the fixed roof opening. Each retractable roof section is supported on 4 electrically driven 4 wheel bogies capable of opening or closing the roof in about 23 minutes. The bogies run on twin rails mounted on a substantial runway girder.

The tubular framework of each roof section is made up essentially of two primary longitudinal trusses at 12m centres supported on disc bearings at bogie locations, with semi-circular shaped transverse frames at 9.1m centres to support the extremities of the 30m wide suspended roof system.

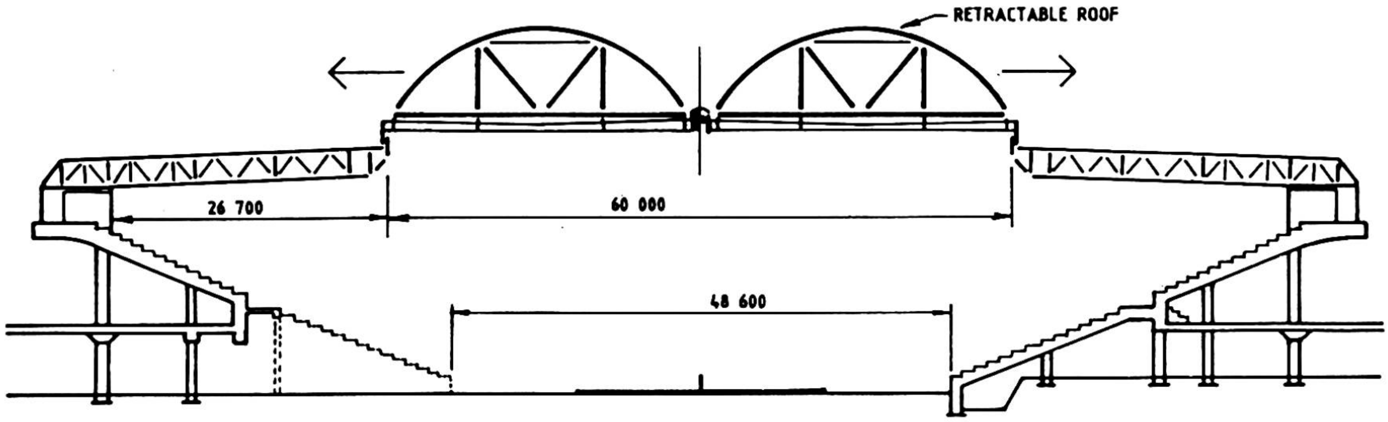


Fig. 2 North-South Section through Stadium

The two runway girders upon which the retractable roof bogies travel are located 98.3m apart and are each 109m in overall length. The term runway girder is used to describe collectively a 760mm x 460mm box girder to which the twin rails are attached and its support system which varies over its length. The runway girder is located primarily within the confines of the fixed roof except for a 20m length exposed at each of its ends. Within the stadium the support is a parallel-chord truss spanning between the shear walls, whilst outside the stadium structure the support is a truss with a curved bottom chord spanning between two 16.2m high braced tubular steel columns.

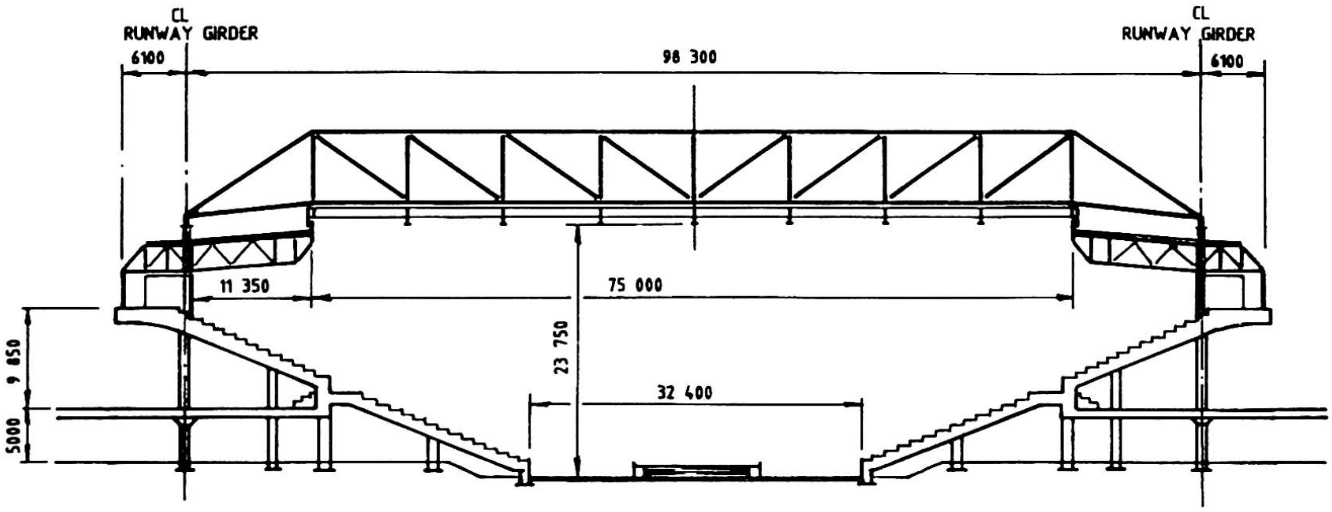


Fig. 3 East-West Section through Stadium

The runway girders are structurally independent of the fixed roof, but are restrained longitudinally by means of disc bearings at the lift wells located at each corner of the stadium.

The retractable roof bogies are supported on two 60 kg rails located 460mm apart directly above the webs of the box girder. The rails are placed on 7mm thick neoprene pads to suppress noise levels.

The total weight of structural steelwork in the retractable roof is 300 tonnes, excluding roof and ceiling purlins and the total weight of structural steelwork in the runway girder system is 190 tonnes, including the external support columns.

## 3.2 Design

The retractable roof was analysed for vertical and horizontal loading as a 3-dimensional space frame.

The critical wind loading case for the retractable roof occurs with the roof in the fully open position when one corner of the roof is exposed to updraughts.

Each roof truss can accommodate up to 24 tonnes of performance related equipment, suspended from 7 monorail beams located just below ceiling level. Monorail beams have up to 4 no. 3 tonne electric hoists accessed from retractable platforms contained within the fixed roof.

The runway girder system is designed to accommodate lateral and vertical loading from the retractable roof support bogies. Each retractable roof section is supported on disc bearings at each of the four bogies, with one fixed bearing and three undirectional sliding bearings provided. A support system with a single point of translational fixity was adopted to minimise skewing forces normal to the runway girder.

During operating conditions each roof section is driven by only two of the bogies and these in turn are speed synchronised with a multiple control system to ensure that they do not differ in relative position by more than an absolute maximum of 500mm. Operation of the roof is not permitted for winds gusting above 15m/s.

When the roof sections are in the fully opened or closed positions mechanical locks are engaged automatically to ensure that the drive bogies are immobilized for any wind condition.

For the full 210m perimeter of each retractable roof section a unique yet simple sealing system, utilizing various configurations of natural rubber flaps, is provided to weatherproof and acoustically seal the interface between the retractable and fixed roofs. The sealing arrangement is designed to accommodate large vertical and horizontal relative movements between the various components, and to minimise both the forces exerted on conjugate parts and the power requirements of the drive motors.

### 3.3 Fabrication and Erection

The framework for each section of the retractable roof was largely field assembled and welded on site 40m South of the stadium perimeter and subsequently jacked up to final elevation prior to being moved laterally into its permanent position above the fixed roof. The jacking system used for raising each of the 260 tonne roof sections was based on the standard BBR system. The 20m lift was completed in approximately 9 hours.

The primary connections of the main trusses involving up to 7 intersecting tubular sections were generally facilitated by the use of central gusset plates in the plane of the main longitudinal trusses and diaphragms at each node. This form of connection gives a direct means of connection of primary truss members and provides sufficient rigidity to the main tubes to enable the direct tube to tube connection of secondary members.

Following shop assembly and welding of the primary frame nodal assemblies, the erection procedure for each retractable roof section involved assembly and welding of nodes and frame elements between nodes in a sequence from mid-span toward each end. Roof and ceiling purlins and diagonal bracing were then installed with bolts left loose. The structure was then jacked up to a height of 2m, where the roof and ceiling cladding and acoustic insulation were installed and bolts tensioned before jacking the roof to its full height. Temporary runway girders and the bogies were then fixed in place, the roof lowered onto the bogies and driven laterally into its final position.

The longitudinal trusses of each roof frame were precambered upwards by 280mm to accommodate approximately 80% of the full theoretical dead load deflection and this assumption was validated by the actual deflections recorded.

## 4. ACKNOWLEDGEMENTS

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