Brisbane Convention and Exhibition Centre

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INTRODUCTION

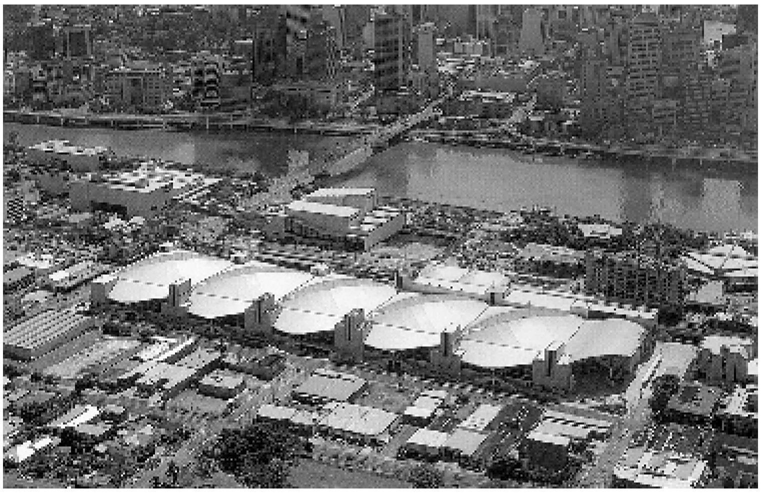
The new Convention and Exhibition Centre in Brisbane, Queensland, was opened to public acclaim in June 1995. The building is vast – over 400m long, up to 150m wide, and 32m tall – but its most individual feature is the roofscape, which breaks down the bulk, occupying more than two complete city blocks, and brings the edges of the building down within reach of its mainly pedestrian visitors. This endows a human scale and gives the sense of craftsmanship and personal input of which the late Peter Rice spoke so eloquently in his 1992 RIBA Gold Medal speech[1], and in his book[2].

The roof is also innovative in its structural action. Following the use of cable or rod–stayed roofs in the 80s, there has been a trend towards steel lattice grid shells. Most of these have used one–way curvature, usually as a simple barrel vault. The Brisbane roofs break new ground by using two–way, anticlastic curvature, which results in a shell of extreme delicacy as it has little propensity to buckle.

The building is even more remarkable given that procurement was by competitive design–and–construct tender with a very short programme. Great credit must be given to the client and design team for their courage to embark upon such a project with such time and budget constraints.

OUTLINE DESCRIPTION

There are five large halls, each 72m x 72m in plan with 14m clear ceiling heights. Four are dedicated exhibition halls; the other (the Great Hall) can be used in exhibition, convention, theatre or banquet modes. It incorporates over 3000 seats, both fixed and raiseable in tiers; the latter can be hoisted to roof level out of the way for exhibition or banquet modes. The halls are augmented by a 2200m^2 ballroom; outdoor exhibition space; a series of meeting rooms from 30m^2 to 1000m^2; associated support facilities including a central kitchen that can cope with meals for up to 8000; and basement parking for 1600 cars. All halls are directly accessible to vehicular traffic via an elevated service road. The total floor area exceeds 110 000m^2, which makes the centre the largest building project ever undertaken in Queensland.



View towards north east with Brisbane River and city centre beyond. From right to left: principal elements are the main foyer, the Great Hall and Exhibition Halls 1–4. In front is the concourse, with the loading dock behind halls 2, 3, and 4. To the right of the loading dock is the railway plaza structure supporting the twin roofs of the ballroom behind hall 1 and the flat–roofed main meeting room and pre–function terrace behind the Great Hall. The complex occupies two city blocks with the dividing street passing under hall 2 and car parking on both sides under halls 1,3 and 4.

TENDER

The Queensland Government identified some years ago that the state's share of Australia's convention market was in decline due to the capital's lack of international–standard facilities. It was decided that a new exhibition and convention centre should be built and in late 1992 tenders were called for its design and construction. Arups were invited to join the team led by Leighton Contractors with Philip Cox Richardson Rayner in association with Peddle Thorp as architects.

The required area of exhibition and conference halls only just fitted within the surrounding roads so the basic plan was reasonably obvious – the row of five 72m square spaces with 14m clear headroom, interconnected by enormous doors allowing for independent or combined use. The halls have entry foyers for the public on one side and service access for heavy goods vehicles on the other. Essentially it was a big shed, which could to all functional intents and purposes have been much the same as an aircraft hangar or high bay warehouse.

All Asia Pacific exhibition centres compete for the same market, so each strives for some positive visual identification or public appeal. The main opportunity for differentiation is in roof design. The typical warehouse or hangar–style deep truss is cheapest, but for a small increase in structural cost many other systems become feasible. The choice is largely aesthetic but must also consider the site and its ground conditions and boundary constraints; cable–stayed designs, for example, are not appropriate if permanent tension anchorages cannot easily be constructed, nor if there is insufficient room for back stays. The actual choice of roof system therefore comes from an intimate collaboration between the architect and structural engineer, both responding to the particular site.

For this project the design team decided on a roof shape recalling some of the free–form characteristics of the fabric structures that Brisbane people fondly remember from World Expo 88, held on the same site. Interstate rivalry made it essential that the Brisbane centre's roof could not be confused with the Darling Harbour Exhibition Centre in Sydney, also designed by Cox and Arups in the mid–'80s. Coupled with this desire for a striking design was an absolute value–for–money requirement, and avoidance of any cost premium or risk associated with innovation.

These potentially conflicting objectives were brought together with the proposal to use doubly–curved steel grid shells as the primary roof structure, arranged to form a modulated roofscape which echoed the distant hills to the south.

To benchmark the proposed roof, a conventional gabled truss was designed. This demonstrated that the lightness and visual appeal of the preferred design more than compensated for the additional complexity and marginal increase in cost. A further advantage of the thin shell was its ability to accommodate very tall exhibits either side of the diagonal truss. The decision to proceed with these complex shells, based on a few weeks of hurried work, set the course for the future. If Government accepted the tender, the design team would have to provide the promised building for the offered price within the allocated programme.

Left: From street level, the service towers clearly define the halls.

Right: From a distance the roof provides the principal visual impact

After detailed evaluation and assessment of bids from five short–listed tenderers, the Government awarded the contract in February 1993 to Leighton Contractors. The special roof form is said to have had a major influence on this outcome. Upon contract award the team had four weeks to design the footings with a further eight weeks before the roof steelwork went to tender.

SUBSTRUCTURE

The site is just south of Brisbane's Central Business District in the north–west corner of the South Bank redevelopment area. Bounded by Glenelg, Merivale and Melbourne Streets and the main New South Wales to Queensland railway, it was once part of the South Brisbane Railway goods yards.

In geotechnical terms it is highly variable, due to the nearby Brisbane River and the presence of buried creek channels. The soil profile comprises variable strength rock (Brisbane schist), overlain by soft clays and sand up to 22m deep, with a high water table. The site is subject to periodic river and local flooding.

The high water table and variable depth to rock forced a combination of foundation types. Driven precast concrete piles were used over most of the site, with short bored reinforced concrete piers and conventional pad and strip footings used where rock levels permitted. Where possible, basement extents and column locations were selected to minimise temporary shoring, in particular by the existing railway embankment. Foundations were also arranged to minimise clashes with known buried obstructions from now–demolished buildings.

Conventional block and reinforced concrete retaining walls were used except at the site's south–east corner, where the platform was cut very close to the inter–State rail lines. Here, soil nails were used through the relatively unstable ash–rich embankment.

SERVICE TOWERS

An advantage of the chosen roof type is that it is a fully–resolved, simply–supported structure only requiring these primary supports in the four corners of each hall. allowed all the service elements to be concentrated into towers containing concrete shafts that stabilise the building much like the central service core of a high rise building. They also break up the building's enormous length, define the individual halls, provide a rectilinear contrast to the undulating roofscape, and house plantrooms and other ancillary facilities.

The towers vary in size, standing up to 28m above ground, or 24m above exhibition level. Whilst the lower levels are in situ concrete, above the roof supports the towers are largely steel–framed with composite floor slabs supported on profiled steel decking. To achieve the desired sculptured appearance, the entire tower structure is clad with precast concrete panels. Each complete tower was designed to be built independently of the hall roofs and to provide lateral restraint to concourse and loading dock roofs so that these would be independent of the hall roofs. This articulation provided maximum flexibility for detailed services co–ordination in the towers to be finalised whilst the roofs were being erected.

FLOOR SLABS

All ground slabs are of conventional reinforced concrete, isolated from columns and designed for the variable support conditions offered by the existing subgrade.

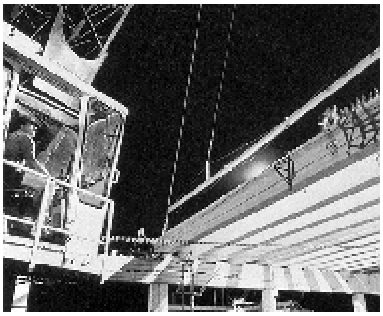
Numerous schemes were considered for the main suspended slabs, including reinforced or prestressed concrete flat slabs and band beams, composite steel construction, and precast concrete. The cheapest were reinforced concrete flat slabs, varying in thickness from 220mm in suspended car park areas to 350mm for the most heavily loaded exhibition areas (20kPa). At first prestressed flat slab options seemed competitive, but the plan extent of areas between expansion joints – typically 72m x 50m – and the need to rigidly connect slabs to the relatively stiff roof support shafts at the ends of the 72m sections ruled them out, due to their higher long–term axial movements and resulting restrictions on pour sequences.

Added benefits of the selected scheme, with its thicker slabs, included being able to accommodate exhibition service pits without soffit steps, and flexibility for many changes in position of service penetrations and set–downs before, during, and after construction.

Slab types in the upper levels of the building varied, with reinforced concrete beam/slab, prestressed concrete band beams and transfer beams, and steel–framed composite floor construction all used as appropriate to construction access and usage of the areas involved.

RAILWAY PLAZA STRUCTURE

The brief did not include the Ballroom until after the contract was let. This was to be built over the adjacent railway, thus also providing a connection to the existing South Bank redevelopment to the north. To support this extension, a 200m–long bridge structure – the plaza – was designed, and built over the existing suburban and interstate railway lines near the main building. Whilst preliminary studies indicated that intermediate support to the plaza structure could be provided by central piers between tracks over part of its length, the final design comprised a total of 89 precast, prestressed bridge girders, each weighing 42 tonnes and spanning the full 38m width of the railway corridor. The girders are the longest possible of their type, and needed the largest casting bed available to be extended. These enormous beams had to be thoroughly investigated for their stability whilst being lifted, as well as in their final configuration.



By eliminating intermediate supports, and locating column lines well away from the tracks, restrictions on working hours and methods dictated by track proximity were reduced. As a result, piers and headstocks were readily constructed during normal working hours and the prefabricated bridge girders erected during regular track close–down periods at a rate of between three and five girders a night. A 200 tonne crawler crane was used – and removed during the day to allow the railway to resume.

The girders act compositely with a cast in situ reinforced concrete deck, the whole assemblage supporting major superstructure elements including the $2200m^2$, 15m high ballroom, pre–function terrace, pedestrian plaza and a major meeting room. The closeness of the rail tracks below posed a potential acoustic problem for the ballroom and meeting room, so the deck structure was completely isolated from headstock supports via bearings. In addition, a floating floor in the ballroom and meeting room area was provided,and isolated in turn from the deck structure via a further series of bearings.

HALL ROOFS

The roofs are supported by a structure comprising six elements:

- The doubly–curved hyperbolic paraboloid shells, cut and folded about one diagonal, which form most of the roof surface.
- A bowstring truss, triangular in section, which spans 100m diagonally across the hall to support the edges of the shells where they were cut and folded.
- A shear frame comprising the perimeter members plus the truss bottom chord acting as a massive diagonal brace across the 72m x 72m square.
- Two overhead cables which run diagonally across the roof perpendicular to the bowstring truss and connect it to the opposite corners of the roof. This forms the most direct method of preventing the truss rotating about its bottom chord under out–of–balance loading.
- Slender tubular columns along the front and back of the roof to lightly support the delicate shell edges.
- Trusses spanning from side to side between the shafts to provide unimpeded communication between adjacent halls; they both support the roof edge and also hang the massive openable doors. They have an open V–section to allow each roof to move relatively independently under thermal loads.

This combination of elements creates a fully resolved roof structure which delivers 90% of the applied loads to the two support shafts at each end of the diagonal truss. The structure is clad with simple open channel purlins supporting profiled metal roof sheeting over fibreglass insulation. The perforated ceiling is placed underneath the purlins but above the supporting structure. The opportunity was taken to increase the roof's visual impact by running cladding down and up the inclined faces of the truss to open a huge diagonal gash in the roof surface.

Following the slightly cluttered result of the underside of the roof at Darling Harbour Exhibition Centre, efforts were made to make Brisbane tidier. The air ducts were confined to bulkheads around the roof perimeter, or within the envelope of the spine truss. Only the light fittings were directly hung from the shell, and lifting points for exhibition loads of up to 3 tonnes were provided at each node point.

GREAT HALL ROOF

The Great Hall roof, although identical to the other four in external appearance, required a more complex design to support the seating for 3000, which can be raised up by chain blocks attached to the roof, and full–height subdividing operable doors. Also, its cladding contained a mass layer to provide better acoustic performance. As a result, the design gravity load for the Great Hall roof was twice that for the other halls.

Despite this dramatic increase, the basic shell and bowstring truss were retained, but the system was strengthened with an additional grid of tension/compression members at eaves level. This allowed the arch and catenary members to act independently as tied arches and propped catenaries, which removes load from the truss and delivers it instead to the short columns around the perimeter of the hall. It also provides a grid of ceiling members to reduce the apparent ceiling height to proportions appropriate to the halls when subdivided.

ROOF LOADS

Special loading criteria had to be considered in the design of the roof structures. Imposed loads had to be large enough to cater for the most ambitious exhibitions, such as a 747 jet hung from the roofs. The Great Hall roof also required additional strength for the raisable floors, additional subdividing walls, and a multiplicity of roof–mounted catwalks, lighting grids, and other services.

The wind loading on the building was of special concern due to Brisbane's near cyclonic winds. The very light shell roofs are subject to substantial net uplift forces, the extent of which were quantified by a wind tunnel test which incorporated time and spatial averaging to generate realistic estimates of aggregate loads. The testing revealed substantially higher uplifts than the values initially derived from the Australian Wind Code and required intensive redesign, as the results became available only shortly before fabrication was due to commence.

A variety of analytical techniques were used in the design of the hall roofs. Initial non–linear analyses using Arups' *Fablon* program were carried out to check buckling under uniform and out–of–balance load cases. Once the non–linear effects were quantified, detailed linear analysis of single and multi–hall models was used to design individual members with appropriate load magnification to allow for the non–linear effects. Finally, the approximate ultimate collapse behaviour of the roof was determined by *Fablon* using all its facilities for elasto–plastic behaviour together with elastic buckling. This gave the designers a measure of additional comfort.

At all times after the contract was awarded, the total tonnage of roof steel had to be maintained. If some elements were found to require strengthening, other elements had to be reduced by an equal amount. The calculations for the roof were independently reviewed by Arups' Perth office as part of the project's quality management. This review determined that every member was being used to at least 90% of its capacity. The result is a roof in which the shell elements weigh a mere 25kg/m^2, and the total weight, including the bowstring truss and perimeter frame, is only 35kg/m^2.

ROOF STEEL SECTIONS

The preliminary design was intended to utilise circular hollow sections throughout the roof. However to simplify detailing and allow the steelwork to be more competitively tendered, the tubes were changed to more conventional universal hot rolled sections. The catenaries, which are continuously curved and support straight purlins, were changed to a universal beam section, and universal columns were used for the arches which are straight between node points and simply bolted to the catenaries. To control the effective length under compression of these I–shaped sections, the bracing was shifted from a conventional cross–brace pattern to an offset diamond pattern, which supports the members about their weak axis at mid–span. It also tidies up the detailing by giving a straight crossover junction at the joint between the catenary and arch members, and a dissociated X–form where the brace members come in. The alternative would have had eight members all converging on one point in space.

The truss chords and perimeter members are tubular, to clarify the connections with members arriving at various positions. During detailed analysis, it became apparent that the shell performance was significantly affected by the stiffness of the perimeter shear frame. To stiffen the latter cost–effectively, the perimeter members were filled with concrete and the truss lower chord was augmented by 12 50mm internal diameter reinforcing bars.

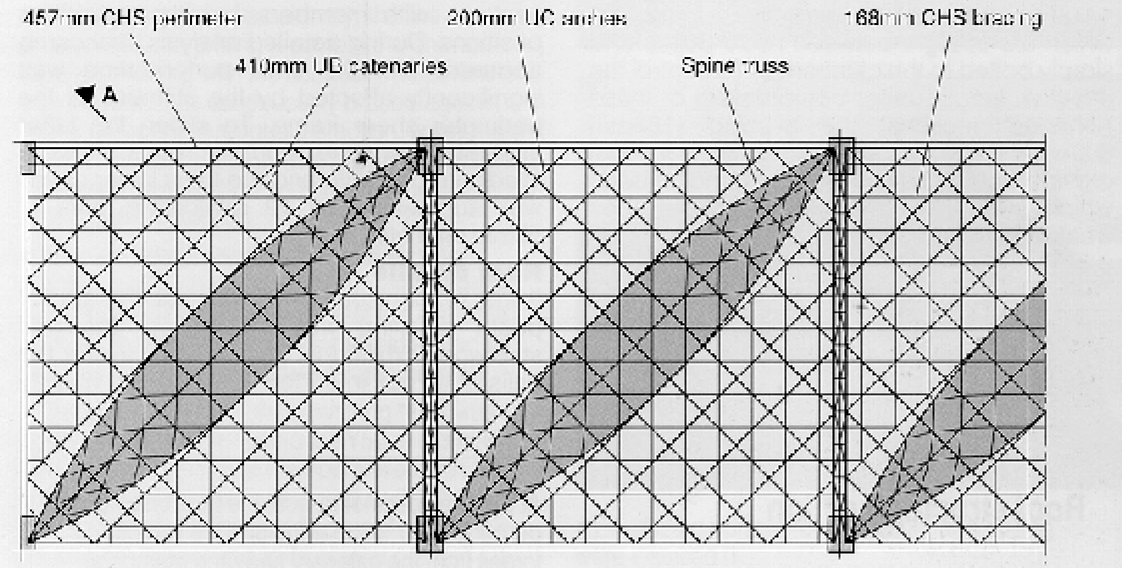
ROOF DETAILS

It was recognised from the outset that appropriate detailing was the key to the roof steelwork. Whilst this can be inside the halls, it is not intended to compete visually with the exhibits, so simple neat details which aided construction were devised.

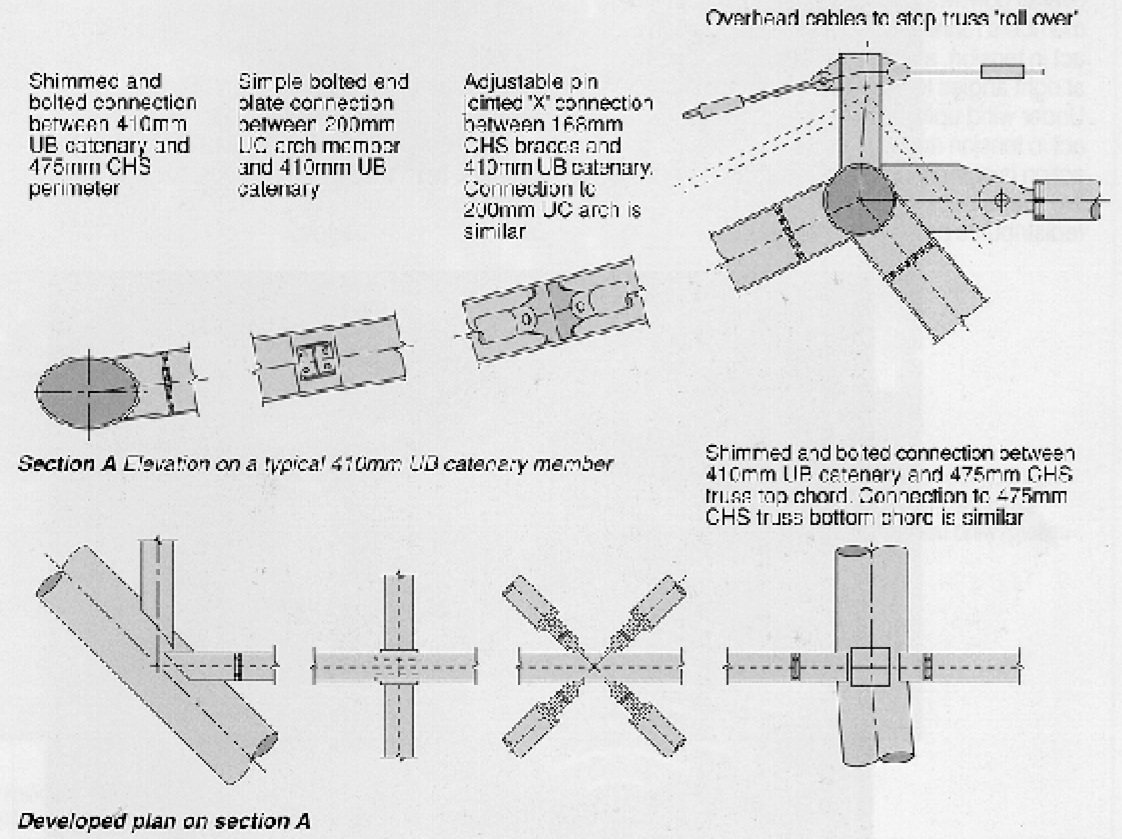
Most of the connections are simple bolted end plate connections within the depth of the sections. Shims are provided to take up length tolerance and the end plates are sufficiently flexible to absorb alignment tolerances by local plate flexure. To both provide this flexibility and minimise use of material, all end plates were designed using yield line techniques, which were also employed to minimise the internal stiffening of tubular sections where the main roof members try to punch into the relatively thin walls of the perimeter tubes.

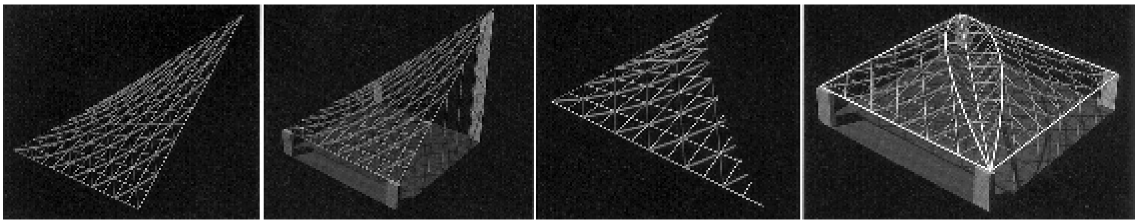
The diamond bracing members were tubes, terminating in classic pin connections. As these members carried relatively light loads, the investment in a more articulate detail was worth while in terms of the clarity provided at an otherwise awkward skew junction. One end of each brace had a shimming adjustment made possible by the use of high strength cap screws.

Each corner of the roof was supported on the reinforced concrete service shafts by elastomeric PTFE/stainless steel bearings. One of these was fixed in location, two were completely free to slide, and the fourth was guided in one direction only. This arrangement gives complete freedom for the roof to expand and contract under thermal loads.



11 Above: Part roof structural plan. 12 Below: Roof steelwork details.



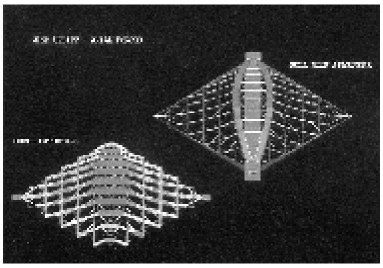


ROOF GEOMETRY

The preferred geometric form for the individual hall roofs was the hyperbolic paraboloid, a pure membrane form evocative of the fabric structures at Expo 88. A hypar is the surface formed when ruling straight lines between edges of a square in which one corner has been raised above the level of the other three. At approximately 45 to these straight line generators (shown in grey) are the lines of principal curvature which are equal and opposite (blue and red).

To develop sufficient curvature to be structurally efficient over the 72m x 72m hall, one corner would have to rise by 60m relative to the others. This would have given an unnecessarily large internal volume and resulted in massive and expensive perimeter walls. Instead the surface was cut along an inclined diagonal plane and folded down about the cut diagonal. The result was the same efficient shell but now with uniform, minimum height walls and a rise of only 10m to the centre of the cut edge.

The halves are joined together by a triangular section bowstring spine truss which spans 100m diagonally across the hall and supports the half–shells along their cut edge. The whole is trimmed by a perimeter element.

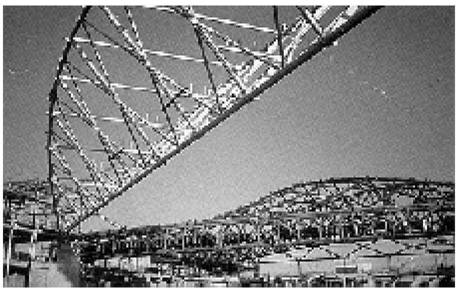


ROOF STRUCTURAL ACTION

The roof shell action is accomplished by using tension and compression members running along the lines of principal curvature. Under overall downward loading, the curved catenary' members running down from the truss to the perimeter act in tension, and the faceted arch' members at right angles to the catenaries are in compression. Under uplift from the wind, the compression members act in tension and vice versa. The structural action is completed by the provision of bracing which controls the buckling behaviour of the shell and also redistributes patch wind loads.

At the shell perimeter, both the horizontal forces perpendicular to the edge and the vertical forces from the catenary and arch members cancel out, leaving only a force in the direction of the perimeter itself. This is resisted by the perimeter of the roof, braced diagonally by the bottom chord of the spine truss, acting as a shear frame.

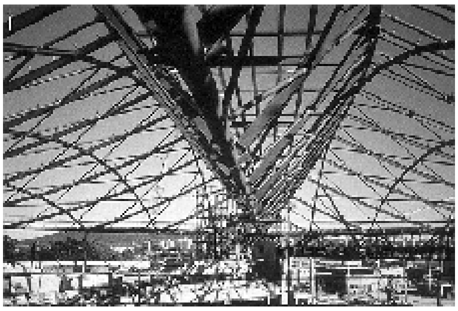
The net result of these primary actions is to deliver almost all of the applied load to the truss and thence to the concrete shafts at each end of it. The perimeter columns could thus be very slender and elegant, as they only support about 10% of the total roof load.

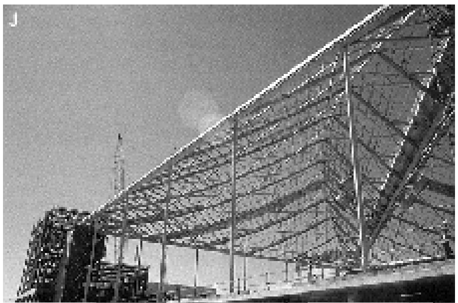


ERECTION OF SHELL ROOFS

The erection sequence and method were carefully thought out and calculated in advance, and then executed rapidly on site. A simple sequence of steps was followed to erect a typical roof shell:

- The bowstring spine truss was assembled at slab level into four pieces. These were then lifted onto temporary supports and connected together with a predetermined pre–camber.





- The pre–cambered V–truss between halls was erected along with the tubular perimeter members and supporting columns.

- Overhead cables were installed to prevent the spine truss from rolling over. The truss could then be de–propped and no further temporary works were required.The catenary members were assembled at ground level into continuous arcs up to 40m long. They were then draped progressively from the spine truss, working from the centre outwards. Each catenary was shimmed equally at each end to obtain a pre–determined sag at its midpoint for that particular member in the erection sequence. For the entire roof pre–erection analysis was performed, in which the erection method was reversed and members were removed sequentially so that the correct starting point for each and every catenary member could be determined. This simple level measurement was the only piece of surveying and geometric control required during the entire roof erection operation.

- After the erection of a catenary, the line of members which made up a complete arch was installed, starting with the shortest. By this means the perimeter member was continuously braced against lateral deflection throughout the erection process without the need for any lateral propping. The arch members were fabricated slightly short and shimmed just to fit the actual gap on erection.
- After all catenary and arch members were erected, the bracing members were installed, using their built–in adjustment to fit the available gaps. At this stage the initially pre–cambered roof had descended to its theoretical geometry.
- The bottom chord of the bowstring truss was lightly post–tensioned and the perimeter members filled with concrete. This slightly pre–cambered and stiffened the roof, so that under the self–weight of the cladding it once again descended to its correct position.
- Finally, the purlins, roof sheeting and ceiling were installed.

FOYER ROOF

The wave form foyer roof is approximately 45m wide and up to 90m long. The supporting structure consists of curved universal beam sections supported on columns within the foyer, trussed mullions on the entry glass line, and a single tree' by the main entry stairs. A tubular steel truss supports the leading edge of the roof spanning 32m from the tree to the adjacent service tower. The roof is braced at lift core locations, and separated from surrounding structures by perimeter expansion joints. The foyer roof is clad with lightweight curved profiled steel sheeting similar to the hall roofs.

CONCOURSE AND LOADING DOCK ROOFS

These appear as projections of the hall roof geometry – an extension of the hyperbolic paraboloid shape. In them the primary structure follows the straight lines which define the surface. The twisted surface is therefore utterly conventional in its structural action, using simple steel beams, purlins and bracing. The beams are supported adjacent to hall perimeters, and cantilever out over the concourse glazing line and loading dock roof support trusses respectively. Simple universal beam rafters are used together with diamond pattern tubular bracing to match hall roof detailing.

BALLROOM ROOF

The form of the two roofs to the 2200m^2 ballroom is somewhat similar to the main hall roofs, but on a smaller scale and with a single ridge line each. With a span of roughly half the main halls, a two–way spanning structure primarily dependent on bending is feasible; there is no need to develop more complex shell action. As for the foyer roofs, straight universal beams are set in both directions along the straight line generators of the hypar surface. These meet at a simple tubular ridge member arching diagonally from one corner to the other. The common edge shared by the two modules is supported by a tubular steel truss which supports a subdividing operable wall. The roofline extends out to form awnings around three sides of the ballroom.

CONSTRUCTION

In true fast–track fashion, foundations were designed and constructed well in advance of the design of upper levels of the building. Physical separation of major structural components via expansion joints – for example, isolation of the hall roofs from surrounding roofs – played a large role in allowing the building to be readily divided into manageable packages for tender, sub–contract, and construction purposes.

CONCLUSION

The centre is undoubtedly regarded as one of Brisbane's most valuable assets. For its $170M cost is expected to inject $800M into the Queensland economy in the first 10 years of operation, boosting the tourism, hospitality and entertainment industries, and opening up a whole range of business and investment possibilities in the city. Further, as a landmark image the BCEC will portray Brisbane to the rest of the world as a modern, thriving community with an identity of its own. The centre has already received the inaugural BHP Steel Award for Architecture, the biennial National Merit Award for Structures from the Association of Consulting Engineers Australia, and joined Sydney Opera House and Sydney Football Stadium among other Arup projects in receiving a Special Award from the UK Institution of Structural Engineers. It has been selected to be the venue for the Royal Australian Institute of Architects National Awards ceremony – for which it is unfortunately not eligible until next year.

Projects like this clearly demonstrate that Australia has the ability to design and construct products of the highest quality, allowing it to take its place as a respected member of the world's building industry.

PROGRAMME

November 1992	Pre–tender design
March 1993	Design and construct contract awarded
March 1993	Earthworks tendered
April 1993	Earthworks commenced, foundations tendered
June 1993	Hall roof steelwork tendered
August 1993	Towers and other roof steelwork tendered
September 1993	Hall roof steelwork subcontract awarded
November 1993	Towers and other roof steelwork awarded
December 1993	Railway plaza girders erection complete
January 1994	Hall roof steelwork erection commenced
May 1994	Concrete works completed
May 1994	Ballroom roof completed
June 1994	First hall roof completed
April 1995	Partial handover of completed building to operator
June 1995	Official opening of the centre.

REFERENCES

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(2) RICE, P. An Engineer Imagines.

CREDITS

Client:

QBuild Project Services as agent for Queensland Government

Project manager:

Leighton Contractors Pty Ltd

Architect:

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in association with Peddle Thorp Architects

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Ove Arup & Partners Australia Ian Ainsworth, Paul Callum, Christine Capitanio, Tom Dawes, Frank Gargano, Stewart Hobbs, Chau Luu, Tom Mulvaney, Gary Robertson, Barry Robson, Andrea Ryan, Bill Short, Robert Thompson, Warwick Walbran (structure)

Tristram Carfrae, Angus Johnson, Alan Shuttleworth, Mark Trueman (roof structure)

Peter Burnton, Robert Donnan (civil structures)

Kirsten Bell, Frank Vromans (civil)

Paul Wallis (geotechnical)

Trecy Boyd, Andrew Douglas, Graeme Krisanski (transport)

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Norman Disney & Young

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Hall roof steelwork sub–contractor:

Evans Deakin Industries

Tower and other steelwork sub–contractor:

Beenleigh Steel Fabrications