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Sydney Opera House – quality, quality, quality!

Introduction

The Sydney Opera House is undoubtedly Australia's most iconic building, and one of the most recognised buildings in the world. Frank Gehry said of this building that it 'changed the image of an entire country'.[1]

The Sydney Opera House was included on the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage List under the World Heritage Convention in 2007, placing it alongside the Taj Mahal, the ancient pyramids of Egypt and the Great Wall of China as one of the most outstanding places on earth. The UNESCO report said: 'Sydney Opera House stands by itself as one of the indisputable masterpieces of human creativity, not only in the 20th century but in the history of humankind.'[2]

The history of the procurement, design and construction of this building is a rich tapestry of events, containing many issues of interest to construction lawyers more than half a century on. Of the triad of issues that make up every construction project – time, cost and quality – the Sydney Opera House demonstrated both the consequences of focusing almost exclusively on quality (initially), and subsequently of elevating the requirements of time and cost over quality.

Procurement

The concept of a Sydney Opera House was promoted by influential people from the late 1940s, but it took a visionary Premier of New South Wales to turn the concept into a reality.

In 1955, the government announced that Bennelong Point was the site for the new Opera House. At that time, it was occupied by a tram shed, built at the turn of the 20th century.

After taking advice from the Royal Australian Institute of Architects, a worldwide architectural competition was held in 1956. The winning entry was designed by Danish architect Jørn Utzon, who was appointed the architect for the project.

The Sydney Opera House was procured in three stages:

- Stage 1: foundations, substructure and podium;
- Stage 2: the 'shells' enclosing the performance halls and restaurant; and
- Stage 3: the interiors.

The initial 1957 estimate for construction of the Sydney Opera House was AUS$7m and about five years, based on the estimate of a quantity surveyor who had no experience with this type of construction. To be fair, no one had any experience with this type of construction, because nothing like this had ever been built before. However, this initial estimate was the source of ongoing public and political controversy, as the cost and time of construction continued to expand.

The building was funded by the Sydney Opera House lottery, established in 1957 before any construction had commenced, and the income from this lottery eventually paid for the entire cost of the building.[3]

Following a change of government in 1965, the incoming Minister of Works sought to exercise more government control, purportedly to better manage the cost and time of construction. In the event, Utzon resigned, and the design and construction of Stage 3 was carried out under another architect. The result was that the interiors of the Sydney Opera House were not completed in accordance with Utzon's design concept.

Design concept

In November 1954, the 'father' of the Opera House, Premier Joe Cahill, appointed a small working committee to progress the project and make recommendations to government. In February 1956, a 25-page competition booklet was released to the world's architects, who were required to register their interest by mid-March. Eight hundred and eighty-one competitors registered, representing 45 countries. By the closing date of 3 December 1956, 222 entries had been received from 28 countries, including 65 from Australia and 51 from England.

The judging panel comprised four architects, two Australian and two world renowned architects from overseas – one of a modern outlook and one of a conservative outlook. Judging took place over ten days, and winning entry number 218 was announced on 29 January 1957. Jørn Utzon's prize was AUS$10,000.

The *Sydney Morning Herald's* (SMH) headline was 'Dane's Controversial Design Wins Opera House Contest'. According to that newspaper, the chairman of the judging panel stated that quantitative surveyors had examined the plans of the ten leading entries and the winning entry was by far the cheapest to build. The two international judges said that, although the drawings of the winning design were simple to the point of being diagrammatic, 'we are convinced that they present a concept of an Opera House which is capable of being one of the great buildings of the world. Because of its very originality, it is clearly a controversial design. We are, however, absolutely convinced about its merits.'

The sketches were free-form, and not based on any geometrical construct. There had been no engineering input.

Utzon's simple, prize-winning drawings 'emphasise the contrast of a solid base, terraced with the stepped auditorium levels carried across the width of the platform to create a sculptured terrain, and floating shell roofs which step up to accommodate the volumes within them'.[4]

His conception was of the roof 'shells' as clouds that appear to float above the platform without touching it. In the competition drawings, the concrete shells were a mere 100mm thick. In the postwar period, when building materials were in short supply, thin concrete shell structures became very popular. Their economy derives from resisting external forces by compression within the thickness of the shell, however, they are unable to resist bending arising from discontinuities of shape.

Utzon's sketches 'showed roof shapes which were lyrical and beautiful. It was a sculptural building, elegant in appearance from every aspect, sheer joy to behold. The roof shapes were described at the time as poetry, shapes the like of which had never been built before. They broke all the engineering rules of shell design.'[5] Significantly, the sketches were free-form, and not based on any geometrical construct. There had been no engineering input prior to the announcement of the winning shell design. It is apparent that the judge's comment that Utzon's design would be the cheapest to build was based on the concept of thin, concrete shells.

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Structural design

The architect and engineers worked together to derive mathematically definable shapes for the shells that were then capable of being analysed. The mathematical calculations involved in analysing the stresses and deflections in just one defined geometrical shape of 'shell' are complicated and time-consuming.

From 1958 to 1963, the original freehand drawn, single skin, reinforced concrete shells went through 11 iterations before the final design was complete with all working drawings. These iterations included consideration of parabolic, circular and ellipsoidal schemes, before the final spherical scheme was adopted. The late 1961 conceptual breakthrough that made analysis and construction of the shells feasible and efficient was Utzon's idea of making each member a segment of a sphere of 75m radius. The ribs that make up each main shell all radiate from a point or pole near the support of the shell. They have varying cross sections along their length, but the cross sections of all ribs at the same arc length from the pole are the same. This enabled considerable economies in construction.

Structural concepts investigated included single skin reinforced concrete shells with ribs, double skin reinforced concrete shells with two way ribs and a steel spaceframe with reinforced concrete skin, before finally settling on precast concrete ribs and partial in situ concrete.

Given the complex geometry, there were no analytical precedents to follow, and no routine calculation methods available. The complexity forced the design team to source large-scale computing power.

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In 1958, computers were in their infancy: they were very large, very expensive and did not have user-friendly interfaces. At that stage, there was still a choice between analogue computers and digital computers for carrying out mathematical computations. The use of computers in engineering design offices was unknown, and slide rules were used for most mathematical calculations.

The structural engineers, Ove Arup & Partners, obtained access to the most powerful computers available, at enormous cost. As there was no application software available, the engineers had to write their own software programs from scratch. This entailed considerable risks, such as whether the answers were correct, or the algorithms for the basic geometric functions correctly coded for all extremes of data. While the computer performed complex mathematical calculations in a fraction of the time that humans would have taken, the engineers had the responsibility of ensuring that the resulting designs were consistent with their estimates of construction material performance and equation solution. The Arup engineers had a maxim that is equally applicable today: 'if you don't know the order of magnitude of the answer, don't use the computer'.[6] In other words, computer output should be consistent with what is expected, not implicitly believed and retrospectively justified.

In addition to the calculations for the shells, computers were extensively used for the analysis of the complex prestressed concrete podium beams. These beams were shaped and folded like the hulls of boats, had a kink along their length, and spanned approximately 50m. The complex calculations for these beams ensured that their cross sections were an optimum design, with material where it was most needed.

The complex glass façade infills to the shells also required considerable computation to determine the length of every supporting member, the angle of cut of each piece of glass at its ends, the position of the bolts, the shape of each connection to the shell rib, the size and shape of every sheet of glass, as well as the forces on them.

Arup staff estimated that, by 1967, they had used 2,000 computer hours, work which would have taken an estimated 100 million hours if done manually. The central role of computers in the design of the Sydney Opera House was summed up by the following statement from Ove Arup and Jack Zunz, a partner responsible for the Sydney Opera House project: 'With hindsight, it is felt that the shells would probably not have been built without the use of computers. We could not have produced the mass of information, let alone the analytical work, necessary to erect the building in the time available.'[7]

In addition to the extensive use of computers for calculation, two physical models were tested. A wooden model was tested for wind pressure distribution in the wind tunnels at Southampton University and the National Physical Laboratory London and a 1:60 Perspex roof model was tested at Southampton University. That model was loaded with weights and the stresses measured by means of strain gauges,

Sydney Opera House under construction, 1968. By PhillipC (Flickr) [CC BY 2.0 (http://creativecommons.org/licenses/by/2.0)], via Wikimedia Commons.

recorded at an electrical console. The testing took nine months, and required a computer to analyse the output from the large number of strain gauges.

Construction

Political imperatives dictated that construction at Bennelong Point should start as early as possible, before a forthcoming State election. The tram sheds were demolished in 1958, and construction of Stage 1 (foundations and podium) by Civil & Civic Contractors commenced in March 1959. Included within the Stage 1 works were approximately 1,000 rooms, including theatres, stage areas and public lobbies below the podium level.

Ove Arup & Partners were only engaged in November 1958, and had limited time to carry out the structural design of the foundations and podium to support the as yet undefined shells. Accordingly, the initial foundation design was based on estimates of dead load for thin concrete shells of the order of 100mm thick.

The original cost estimate was AUS$7m, and a five-year construction period.

However, the Opera House shells as ultimately designed were not concrete shells millimetres thick, but massive concrete space frame structures with arch ribs metres thick. The substantially greater weight of concrete structure required a redesign of the already constructed substructure, necessitating driving additional piles at considerable expense. There were also many other design changes as the functions of the building developed while construction was being carried out: a salutary lesson on the consequences of 'fast track' construction, that is, commencing construction before the design is finalised!

In 1963, MR Hornibrook was awarded the contract for Stage 2 – construction of the shells. This contract was let on a cost reimbursement plus fee basis, eminently sensible given the unique nature of the construction task, and the many unknowns. The contractor was involved early so that it could influence the design, and it worked closely with the engineers to develop the construction strategy.

The Stage 2 Contractor had to devise a practical and economical method of constructing the roof. The ribs comprising each shell were made up of a number of precast concrete segments, epoxy glued and post-tensioned together. A total of 2,194 segments were cast in steel forms on site. As each of the segments had the same curvature based on the spherical geometry, the same moulds could be used for segments ranging from the T-shaped sections 1,200mm deep and 400mm wide near the springing, to a Y shaped section 2,033mm deep by 3,660mm wide at the top of the longest rib. Each of these segments had to be lifted by a large crane and temporarily supported prior to completion of an arch. The contractor devised a travelling erection arch that enabled scaffolding to be dispensed with. This comprised a steel lattice truss, curved to the same shape as the roof ribs, and able to telescope and twist to accommodate the ribs of varying length and each half arch lying in a different plane. Design development and testing of this erection arch took 18 months.

The concept and shape of the glass walls changed after Utzon's departure in 1965. Laminated glass was used, though it had never been used before in such sizes. Because of the long delivery time of cut glass from the manufacturer in France, a glass factory was established on site. Slightly oversized rectangular sheets of glass were supplied, and then cut to size on site.

Issues with time and cost

As noted above, the original cost estimate was AUS$7m, and a five-year construction period, based on a quantity surveyor's estimate. At that stage, the roof concept was for thin concrete shells.

Construction of Stage 1 commenced in March 1959. The time and cost of this construction stage was undoubtedly increased by the additional piling required after the actual dead load of the final design was determined. In 1962, a new estimate put the cost of the Opera House at AUS$27.5m. Following the change of government in 1965, the new Minister for Works advised a cost estimate of AUS$49.4m and a completion date of 1969. By 1968, the Minister announced an estimated cost of AUS$85m and opening in 1972. When Queen Elizabeth II opened the Opera House on 20 October 1973, the final cost had reached AUS$100m.

Change of architect and its consequences

The change of government in 1965 resulted in a new Minister of Works with oversight of the Opera House project. There had been considerable media attention and public controversy over the escalating costs. The new Minister was determined to find a solution to the cost escalation, and apparently had very different ideas on how the Opera House was to be completed. Working relations with the architect broke down.

In the face of very large unpaid fees, Utzon wrote to the Minister on 28 February 1966 stating that he had been forced to leave the job. Instead of negotiating an appropriate resolution, the Minister immediately accepted the resignation, and issued a press statement to that effect. Utzon left Australia within a few weeks, never to return. It is interesting to speculate on what the outcome might have been had Utzon had access to rapid adjudication of his fee disputes, as would now be available under security of payment legislation.

In the event, in 1968, Utzon initiated proceedings in the Supreme Court, seeking AUS$350,000 for outstanding fees. This action was settled in 1974 for AUS$46,000. The government and Utzon agreed that neither party was at fault, and that there would be no further claims. The settlement amount brought the total fees earned by Utzon in relation to the architectural work to AUS$1,250,000.[8]

Professional and public opinion was mobilised to try to have Utzon reinstated. Despite a vigourous public campaign conducted over nearly two years and supported by many leading architects, the Minister was unrelenting. A new architect was appointed, Peter Hall, until then with the Public Works Department.

Although it has since transpired that Utzon and Hall did have discussions, the new architect essentially started with a clean sheet of paper, and designed the interiors of the theatres and the glass walls (Stage 3) from scratch. Thus, neither the interiors nor the glass walls are Utzon's concept or designs. All the conceptual work that Utzon had carried out, and his holistic design of exteriors and interiors of the Opera House, came to nothing.

Refurbishment

In 1999, the New South Wales (NSW) government effected a reconciliation with Utzon, and engaged him as design consultant on the Opera House upgrade programme. In 2002, Utzon produced the 'Utzon Design Principles', as a permanent reference for the long-term management and conservation of the building. A conservation management plan incorporating the Utzon Design Principles has been developed that will guide any future adaptation of the Opera House.

The NSW government has committed AUS$200m for the Opera House renewal project, which includes:

- concert hall upgrades to improve acoustics, accessibility, stage and backstage areas, and the replacement of worn out theatre systems;
- a new creative learning centre to give children and young people a space to experiment and learn;
- entry and foyer upgrades to transform the area under the monumental steps into a vibrant, welcoming, car-free entrance and meeting place; and
- a new function centre to celebrate significant events and mark important occasions for community and government events.

When Queen Elizabeth II opened the Opera House… the final cost had reached AUS$100m.

Including several upgrades to the Joan Sutherland Theatre, a total of AUS$273m has been allocated for the first stage of the renewal. One of its important themes is to respect the heritage and integrity of the building in accordance with the Utzon Design Principles, the Conservation Management Plan and consultation with the Eminent Architects Panel and Conservation Council.

Conclusion

Sydney Opera House is not only notable for its unique and world-renowned sculptural architecture: its design and construction was at the cutting edge of available technology. In the words of the engineers, 'it was undoubtedly the first computer-design and building of significant scale which could not have been built without the use of computers.'

Because of its unique shape, none of the traditional details of building or bridge construction applied, and all had to be researched and developed from first principles. Its many 'firsts' included:

- factory manufacture and erection of large precast concrete units;
- pre-calculation of all dimensions down to the positions of the last bolt and hole;
- epoxy jointing of matched concrete segments;
- development of cement grouts based on investigations using radioactive trace elements; and
- large-scale use of walls and roofs with laminated glass.

The architect and engineers' relentless focus on the quality of the building achieved the World Heritage icon that we know today, and the building will be enjoyed by others for hundreds of years. The change of focus to 'controlling' time and cost ultimately did no such thing, and the change of Architect for Stage 3 resulted in interiors and glass walls that are substantially different from Utzon's holistic design concepts.

The international architectural profession recognised Utzon's brilliant design of the Opera House by bestowing on him the world's top architectural award, the Pritzker Prize, in 2003.

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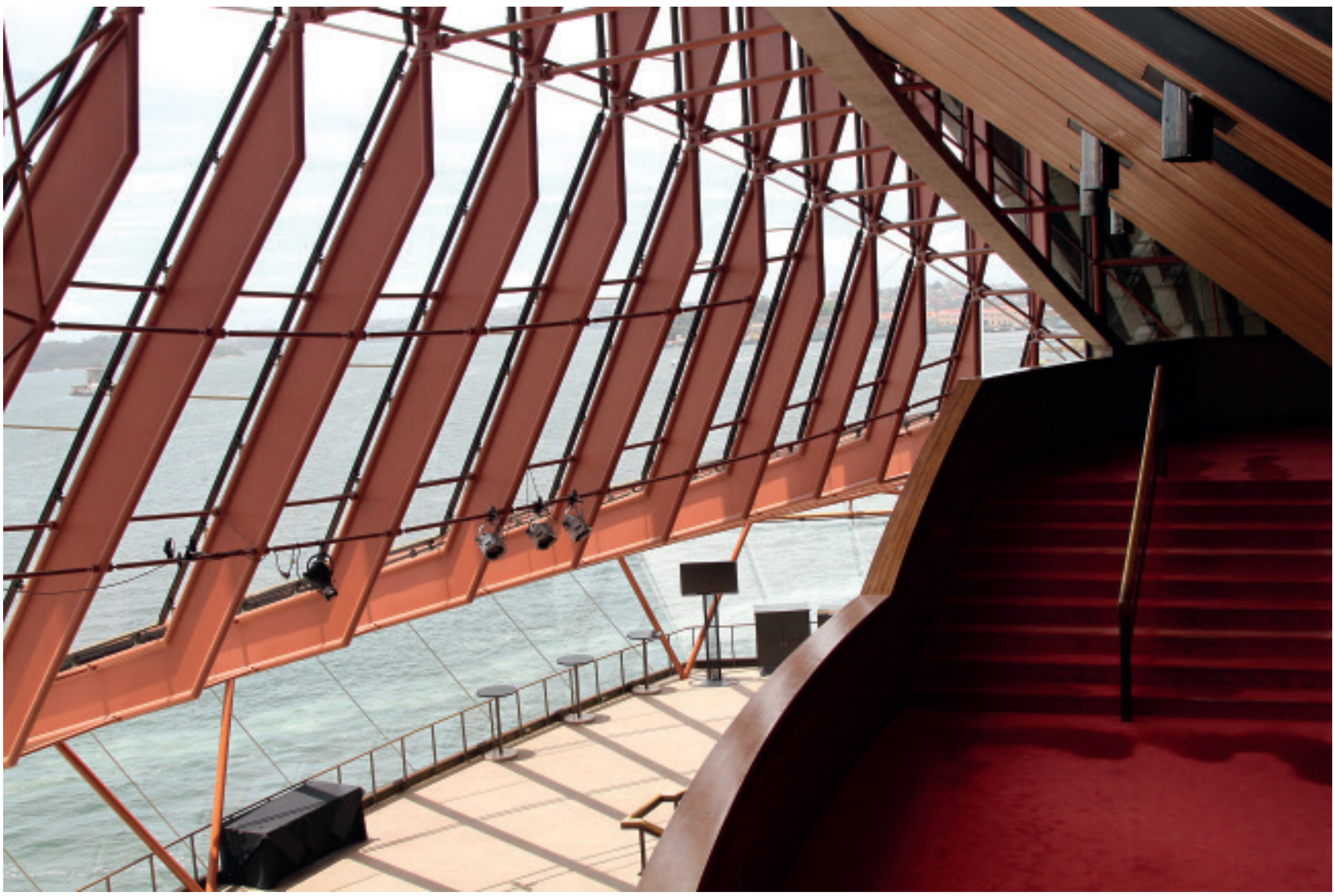
Notes

1 See: www.sydneyoperahouse.com/our-story.html.
2 See: www.sydneyoperahouse.com.au.
3 Daryl Dellora, *Utzon and the Sydney Opera House* (Penguin 2013).
4 On the history of the design, see Anne Watson (ed), *Building a Masterpiece: The Sydney Opera House* (Lund Humphries 2006) 71.
5 *Ibid*, 105.
6 *Ibid*, 89.
7 *Ibid*, 85.
8 'Utzon's Opera House Claim Settled', *The Canberra Times* (23 June 1970).



The foyer of the Opera Theatre in the eastern wing of the Sydney Opera House, showing the internal structure and steel framing of the glass curtain walls, and the views through the windows onto Sydney Harbour. By jjron (Own work) [GFDL 1.2], via Wikimedia Commons.