Danish spheres and Australian falsework: Casting the Sydney Opera House

L. Cardellicchio
University of New South Wales, Sydney, Australia

P. Stracchi
University of Sydney, Sydney, Australia

P. Tombesi
École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
University of Melbourne, Melbourne, Australia

ABSTRACT: By shedding light on the contribution of local ingenuity and craftsmanship in the making of one of the most celebrated buildings in the world, this paper reveals the largely unacknowledged, detailed complexity behind the fabrication of the iconic roof of the Sydney Opera House.

1 INTRODUCTION

“...so far as I can see, it would not be easy to calculate and detail your plans so as to give justice to your ideas with full clarity and still make them economically possible. Nor do I believe you can count on Australian workmen and Australian technical resources being on the same level as the Danish”.

(Ove Arup to Jørn Utzon) (Murray 2004: 12)

Although Jørn Utzon and Ove Arup candidly expressed their reservations on Australian know-how, Australian workers and technical resources were crucial for the construction of the Sydney Opera House (SOH) in the 1960s. Indeed, while it might not have been so evident in the eyes of the two Danes in 1957, Australia possessed a long and solid tradition in concrete, the main material employed in the production of the shells considered the most striking feature of Jørn Utzon’s winning design.

By shedding light on the contribution of local ingenuity and craftsmanship in the making of one of the most celebrated buildings in the world, this paper takes Arup’s words to task, in the process revealing the largely unacknowledged, detailed complexity behind the fabrication of the iconic roof of the SOH.

The first attempts to build with concrete in Australia date from the late 1800s and, by the early 1900s, had also come to concern the erection of important nation-building infrastructures such as the Melbourne Public Library (1906), with its 35 m-diameter octagon surrounded by stacked-book annular and surmounted by what was then the largest reinforced concrete dome in the world (Saunders 1959), or institutional complexes like the Newman College at the University of Melbourne (1917) featuring a rotunda dome built in reinforced concrete with crisscrossing cuspid-like ribs forming structural arches (Turnbull 2004). However, in spite of the formal potential expressed by these structures, reinforced concrete was mainly used as a structural medium and rarely exhibited in building exteriors. Indeed, while concrete was well represented in the Australian construction industry, by the time of the SOH competition it was still often hidden behind brick, stone or terracotta cladding. All-reinforced concrete building was by-and-large limited to civil engineering structures (such as silos, bridges and tanks), and mostly as an in-situ material. In Sydney, concrete was used extensively for maritime works aiming to tame the coastline of the famous city’s harbour, for which precast techniques were also pioneered – the lighthouse at Bradleys Head, Sydney (1904) being one of the most notable and first examples of exposed precast concrete.

With few exceptions – for example, the Knitlock system (Watson 1998) for houses developed by Walter Burley Griffin and David Charles Jenkins in 1917 – it was only after World War II that, with brick and structural steel in short supply, concrete and precast concrete started to be used more widely and exhibited. This was the case of the “Concrete House Project” promoted by the Housing Commission in Victoria, which boosted the development and production of precast elements, culminating in the construction of 30-storey blocks considered to be amongst the most sophisticated precast concrete structures in the world for the time. By the mid-1950s, there were over a dozen concrete manufacturers operating in Australia, as well as many engineers who were beginning to learn the calculation methods required for precast concrete (Concrete in Australia 1977). Alongside its
development, which increased the speed of construction and enabled the reduction of on-site labour, the construction industry looked with great interest at pre-stressing techniques fit to exploit the potential offered by precast modular construction while stabilizing it through post-tensioned high-tensile steel wires.

Post-tensioning made its first appearance in 1953, in the construction of a segmental single-span bridge (21.2 m) at Island Bend, New South Wales. The bridge preceded the renowned Gladesville Bridge over the Parramatta River, completed in 1963, which was laterally pre-stressed with longitudinal post-tensioning, and was showcased as the longest single-span, concrete bridge in the world at the time (O’Connor 1988).

With necessities and economic reasons driving the development of a solid knowledge of concrete, the material started to be used in a variety of ways, capable of fulfilling designers’ aspirations and interests. As a result, from the 1950s, Australia witnessed not only a large use of concrete in architecture but also a varied application of the same: thin concrete shells, off-form concrete structures, and precast panels with local exposed aggregates gained more and more space in the country’s architectural landscape. Among the many buildings, the shell for the Shine Dome, Canberra (1954), the precast hyperbolic paraboloid for the roof of the St Kevin’s Church, Dee Why (1961); the IBM House, Sydney (1964); and Australia Square (1967), the second tallest skyscraper in the world at the time, portray a general idea of the creative use of reinforced concrete in Australian architecture and its construction industry (Stracchi 2019). In New South Wales, the industry-leading builder was Civil & Civic (eventually acquired by Lendlease), a company with a sound know-how of concrete construction (Steward & Taylor 2001). Civil & Civic was in fact behind the design and construction of the Unilever House, the Caltex House and the ICI building, Australia’s first examples of International Style multi-storey buildings, which employed innovative concrete structures and techniques (Concrete in Australia 1977). In 1959, Civil & Civic was appointed as main contractor for the construction of stage I of the SOH – foundations and podium – which included the implementation of the intricate exposed concrete soffit for the entrance concourse.

It was within such an energetic concrete construction culture that Utzon and Arup built their SOH – indeed, a collective enterprise that benefitted not only from the creativity of the two Danish masters but also from the craft of the many Australian concreters and concrete specialists trained on the grounds of the local industry.

Among the extensive body of references and publications about the construction of the SOH, there are comprehensive technical appraisals. One is the report written by Arup Engineers’ central figures Sir Ove Arup and the project lead Sir Jack Zunz, and published in the Arup Journal in October 1973 (Arup & Zunz 1973). The report chronicles the unfolding of different aspects of building the SOH, such as the development of the podium-beams, the evolution of the shells’ geometry to accomplish structural stability and building repetition (the legendary spherical solution), the structural analysis of the roof, and the engineering of the glass walls.

Other studies that examine architecturally significant items include a monograph by the Hornibrook Group, the general contractor of stage II and III (Hornibrook Group 1973), an explanatory account of pictures from the building site (Pomeroy 1984), a “biography” of the spherical solution (Mikami 2001), and a scholarly analysis of the interiors’ development, which focuses on the role played by architect Peter Hall in the completion of the building after Utzon’s resignation (Watson 2017). Indeed, with the exception of an earlier publication by Anne Watson, from 2006 (Watson 2006), no published studies deal with the workers. The story detailed in the literature is mostly hagiographic of the project as a whole – a grand technical synoptic narrative that brings everything together whilst overlooking the micro-details of the trades involved, with their everyday challenges. This is the reason why, notwithstanding the wealth of references about the building, its physical history remains disjointed and anecdotal; by-and-large, the processes involved in its materialization over a period of approximately 15 years have yet to be detailed and organized. This is not a menial task. After all, throughout that time, at least 230 companies were contracted for construction-related services, tens of thousands of people passed through its site gates, union movements grew, and new applications of materials were discovered (Tombesi 2005, 2006; Tombesi et al. 2010; Watson 2006).

This paper is the first outcome of a research project started in 2019 with the aim of contributing to filling this gap. It analyses the contribution of the Australian construction company in charge of stage II to the production of the formworks and the concrete components that are the backbones of the sails of the SOH and considers its working relationship with the engineers from Arup.

2 METHODOLOGY

As suggested, the intellectual contribution of the general contractor in the making of the Sydney Opera House is largely unexplored. This may be partly due to logistical difficulties in locating the material necessary to analyse such contribution, as documents, technical drawings and construction pictures are kept in different locations in the state of New South Wales, Australia: the New South Wales (NSW) State Archives and Records in Kingswood; the Powerhouse Museum, in Ultimo; and the Mitchell Library, a department of the NSW State Library, in central Sydney. While relying on archival investigations for its relevant sources and documents, the research team had to go through a mapping process to locate essential items. Particularly, the emphasis was placed on identifying drawings and reports helpful to clarify how the contractor delivered, on-site, the information contained in the structural
As widely known, the construction of the SOH was structural designer of the SOH, Jack Zunz, wrote: tour notes (SANSW: NRS 18/1566.2), the principal engineer can be seen in several documents. In some on-site Hornibrook as contractor and Arup as structural engineers. The stage II contract covered the structural and civil engineering work involved in erecting the roof structure. The work was administered and managed by Arup as project manager. The fruitful nature of the collaboration between Hornibrook as contractor and Arup as structural engineers can be seen in several documents. In some on-site tour notes (SANSW: NRS 18/1566.2), the principal structural designer of the SOH, Jack Zunz, wrote: “I’d like to say something about the Hornibrook. It is an all Australian firm. Sir Manuel Hornibrook, the founder, started as an artisan and is reputed to have socked his foreman on the jaw, packed his tools and the[n] started the organisation which is now one of the leading civil engineering contracting companies in Australia. MacDonald, Wagner and Priddle, our associated consulting engineers in Sydney, recommended them to us. We in turn recommended that the NSW Government, enter a cost-plus fixed-fee contract with them for the superstructure. For a variety of reasons we didn’t think that it was feasible to follow conventional contractual procedure – chiefly because the method of building would have substantial repercussions on the design and also because vital decisions on design could be taken only when the method of constructing the roof had been agreed upon”. Zunz continues: “Much lip-service is paid to the designer–contractor relationship. In Hornibrook we have found a firm of contractors who are competent, well organised and experienced – and basically good imaginative engineers. We may well ask why we have so rarely worked so closely and harmoniously with a contractor on any other job, anywhere else. For many contractors are competent, well organised – and some are even good imaginative engineers. The answer lies in something that is beyond mere skill and technical competence. It lies in their attitude – which consists of a completely open and unprejudiced assessment of all new problems as they present themselves. And I can testify that in this respect they have been tried and not found wanting”.

The fruitful and integrated collaboration between Arup and Hornibrook is clear by analysing the drawings for the structural projects issued by Arup. Before the involvement of Hornibrook, in 1961, the engineers had considered several possible methods of building the roof, ranging from a fully scaffolded scheme to a fully free spanning one. However, after signing the contract (SANSW: NRS 12686-2-(10/38191)), Hornibrook clearly contributed to many aspects of the very process. Further, a letter, dated 5 April 1962 and included in the contract for stage II, reveals that Corbet Gore and Rob Kynaston (also of Hornibrook) could spend some time in London at Arup to complete the construction scheme. This level of collaboration is also demonstrated in some structural components of the sails. These components are described in drawings issued by Arup but labelled “by Hornibrook”. For instance, the spigots protruding from each rib block of the sails, developed to ease the assembly of the roof, were invented by the general contractor. Moreover, the extensive body of over 2000 drawings issued by Arup for stage II, was not the only way the information was delivered onsite. The authors also found over 300 drawings issued directly by Hornibrook. These drawings focus mainly on the intricate scaffolding systems, the steel arch used to erect the roof and, of course, the formwork systems. These panels, drawn with pencil on tracing paper, define even more precisely the inventive and intellectual role of the general contractor.

4 THE CASTING YARD

To investigate the array of concrete blocks delivered by the casting yard of the SOH and the inherent complexity of such endeavour, it is important to read and analyse the construction scope of the sails, i.e. the architectural element generating the need for it. To this end, one must distinguish between its structural elements. The roofs of the Major and the Minor
Hall of the opera house each consist of three distinctive and structurally independent parts. Each part is formed by three different sets of shells jointed up by segmental arches. For each of these sets, one can identify a shell pointing to the harbour, another shell pointing to the city, and an arched structure connecting the two. The official documents named these parts as follows: the bigger shells are called “main”, the smaller ones are called “louver”; the connecting structure is made of “side shells”. They are in fact held by, or spring from, a tripod-like structure appearing on the outer surface like a fan, and made by arches named “octopus” that represent one of the most irregular parts of the whole roof in terms of geometry.

The shape of the main and louver shells is based on a sphere with a radius of 74.98 m (246 ft) to the outer surface of the structure. Each main shell and louver are part of this sphere, with its foot point at a pole of the sphere, so that each rib is geometrically described by a series of identical great circles. All the main and louver shells consist of several ribs with the exact same curvature but with different lengths. This allows a degree of repetition and segmentation of similar ribs into same components. The cross-section of each rib varies to increase its depth and width from the bottom to the top of the roof. A close “T” shape-like cross-section widens from the base to an open “Y” shape-like at the ridge.

The ribs could in fact be divided into segments. The longest rib is made of 14 components while the shortest one is made of two. Regardless of the rib being analysed, each component located at the same distance from the pole has the same cross-section. This allowed the generation of all the ribs components from the same formwork system containing all the segments in their natural sequence. At the top, each main shell joins a round-arched ridge beam also formed by a series of precast standardizable segments that maintain the same section throughout.

By comparison, the side shells require more parts and a completely different system of formwork than the ridge beam arch. Externally, the octopus arches are recognizable from a warped surface, which provides the visual and physical continuity between the main shells (or the louvers) and the side ones. Therefore, the cross-section of these arches is continuously varying, requiring a different set of formworks for their construction. As with the ribs, the octopus arches were discretized in and assembled with precast segments. These components are assembled by sitting on a first section in concrete cast-in-situ.

Consequently, aside from the pedestals of the main shells and the lower part of the octopus arches, the roof of the SOH is essentially made by precast parts. Specifically, the casting yard produced the following:

- the main shells and louver shells' rib components,
- the crown pieces where the ridges of two shells meet
- the ridge beams’ components
- the octopus arches’ components
- the side shell beams.

Figure 1. The casting yard from the roof of Unilever House. NSW Archives and Records NRS:4_7927 (photographer unknown).

To address the fabrication of such a diverse range of components, the casting yard was divided into two main sections occupying the whole area of Bennelong Point towards the city (Figure 1). The western portion (nearest the wharf) was dedicated to precasting the warped segments of the octopus arches. The eastern portion was for the precasting of standard segments for the main ribs (Figure 2).

5 AUSTRALIAN FORMWORKS

The casting yard layout shows that these two areas were divided by rails used for the operation of two Whirley cranes employed to lift the segments from the formwork. Between the two main areas of the casting yard there was a third area used to cast the sub-components for the blocks supporting the standard ribs. These sub-components were necessary because each standard rib block was cast in several stages to ensure geometric accuracy on-site, and millimetric precision for the contact faces of different components upon their connection.

By analysing the contract for stage II, we understand that the formwork system was entirely engineered and fabricated by the contractor Hornibrook. The contract states:

“It was agreed that formwork for the segments, octopus ribs, panels and other components, because of the complicated nature of the work and the impossibility of obtaining full drawings and specifications to enable tenders to be
called, would be fabricated at M. R. Hornibrook (NSW) Pty. Ltd. Works at Enfield under the conditions laid down in Appendix 3 of the Conditions of Contract”.

To assemble the whole formwork system on-site, Hornibrook produced at least 78 panels drawn in pencil on tracing paper (currently kept at the NSW Archive and Records). The formwork system was designed to allow maximum reuse. In the minutes of the meeting that occurred on-site on 12 November 1962, it is recorded that Gore reported that, on 20 November, they were expecting to run trials for the casting of some concrete ribs. During that time, the formwork was constructed at the contractor’s headquarters in Enfield.

As indicated, each segment was engineered to be cast in small sub-components first. These sub-components were cast in reusable steel moulds, which can be seen in the pictures of the casting yard. Subsequently, the sub-components were inserted into the main formwork system to be jointed together through the final casting phase, producing the block. Sub-components differed in shape and role. The first type was the bulkhead diaphragms designed to be the separation between each rib block.

As it was reported, each rib widens from the base, with the cross-section of each component increasing in depth and width from a solid “T” to an open “Y”. Therefore, several different diaphragms were necessary. As each rib-segment is composed of one bulkhead, and the number of blocks for each rib varies from 3 to 13, there were 13 different types of bulkhead constructed using the same number of steel moulds. The top chord of each rib varies as well. This variation occurs not only according to the height of the component but also according to its position on the shell surface. The majority of the top-chord lids are cross-bracing elements. When lateral stiffening between ribs is necessary, the block is cast with a different top chord, which is recognizable by rectangular pockets oriented like the steel bars. These pockets allowed the lateral bars to be screwed to the concrete blocks. Both of these types of lid were precast in advance using a steel mould placed in the area of the casting yard between the two tracks of the Whirley cranes.

The formworks for the standard ribs were called beds. On-site, there were eight different beds marked with letters (i.e., A, B, C, D, E, F, G, H,) in the official construction documents. In addition, there were four beds for the octopus arches with varying cross-sections, also marked with a letter (i.e., K, L, M, N).

These beds served for the pour of the sides of the rib and arch segments, connecting the diaphragms and the top-chord lids, and forming the different sub-components into a single piece ready to be cured and then assembled into position.

Each bed was made from three different sections, two steel truss moulds and a central web in concrete (Figures 3–4). The steel forms were finished
with plywood of one and one-eighth of an inch. The plywood had a covering of polyester fibre, which gave the concrete an extremely smooth coat. The two sides of the bed were moveable. The steel supports were positioned on tracks which moved in and out over about one foot and were operated hydraulically. The centre concrete wall was permanently fixed and simulated the constant curve of the shell roofs, which were calculated on a radius of 246 feet, eight-and-a-half inches. This central wall acted as the mould for the lowest ceiling point of the cross-rib section, while the truss-side structures changed to accommodate the variation of the rib section. The top of the bed-trusses was completed with a timber walk board, allowing the builders to walk around to manage the different tasks.

The length of the first segment poured into a bed was determined by the position of the concrete bulkhead diaphragm which was placed into the formwork before the pouring of the segment. The reinforcement bars for the segments were folded and assembled in timber cradles and lifted into position in the bed by the Whirley crane. On the side of the bulkhead on which the segment was poured, reinforcing rods were fixed to the diaphragm. These ensured the binding of the bulkhead to the segment in one composite mass. On the other side of the bulkhead, where the second segment was poured, two steel spigots were fixed. The holes the two spigots left in the second segment enabled it to be exactly positioned during the erection. A separating agent was applied, ensuring that the second segment did not become bonded to the bulkhead. Further segments were similarly poured. These first phases focused on fabricating the bottom chord of the rib sections connecting to the diaphragms, which also acted to contain the concrete poured along the length of the bed. For the formwork of the rib sections with the Y-shape, an internal formwork was necessary to cast the side of the components (Figures 5–6). This internal formwork was fixed as a hat on top of the bed section after the reinforcement cage was placed (Figure 7). After the sides and the bottom chord of the rib section was constructed, the precast top-chord lid (often the cross-bracing) was position on the top. A final pouring phase bound the top chord with the rest of the concrete block already cast in the bed. After the final cast, the segments were to be removed from the beds upon reaching a strength of about 3000 psi (approximately 10 days) and remained in the yard until they reached a strength of 6000 psi (approximately 28 days). Before removal of the segments, the two sides of the soffit were hydraulically rolled out to open up the whole formwork system. The Whirley crane then
Three gangs of workers ensured continuity in this phase of the construction. The first group was dedicated to preparing the formwork, the second group was dedicated to pouring the concrete, and the third gang was focused on stripping the components.

6 CONCLUSION

Succinct though it may be at this point of the research, the story of the for-fabrication works put together on-site at the Sydney Opera House tells a tale of work planning and ingenuity that counterbalances the historical myth of the “eureka” moment of the spherical solution of the sails, by highlighting the amount of labour – intellectual as well as physical – required to materialize Utzon’s great idea.

Without taking anything away from the leap of imagination that led to the solution eventually employed, the actual construction of the sails of the SOH owes a huge debt to Australian know-how, as represented in the work by its general contractor, Hornibrook, and its workforce. Indeed, the spherical solution generated a series of significant construction chain challenges, from task identification to site planning, system engineering to shop drawing preparation, work monitoring to quality control, which were all solved through local contribution. Hornibrook did overcome the technical issues posed by the fabrication of all the different parts required through the production of copious, detailed documentation based on and refined via a long period of prototyping work carried out in Australia. Such documentation will necessarily remain a critical object of analysis and reflection in the continuation of the study. At the present point, however, a provisional conclusion can be attempted on fairly safe grounds: for a building justly considered unique and out of time – and as such worthy of world heritage status – the mundane aspects of its realization and the challenges these raised for the industry at the time may well constitute the true gauge of its “concrete” achievements on the ground.

REFERENCES


