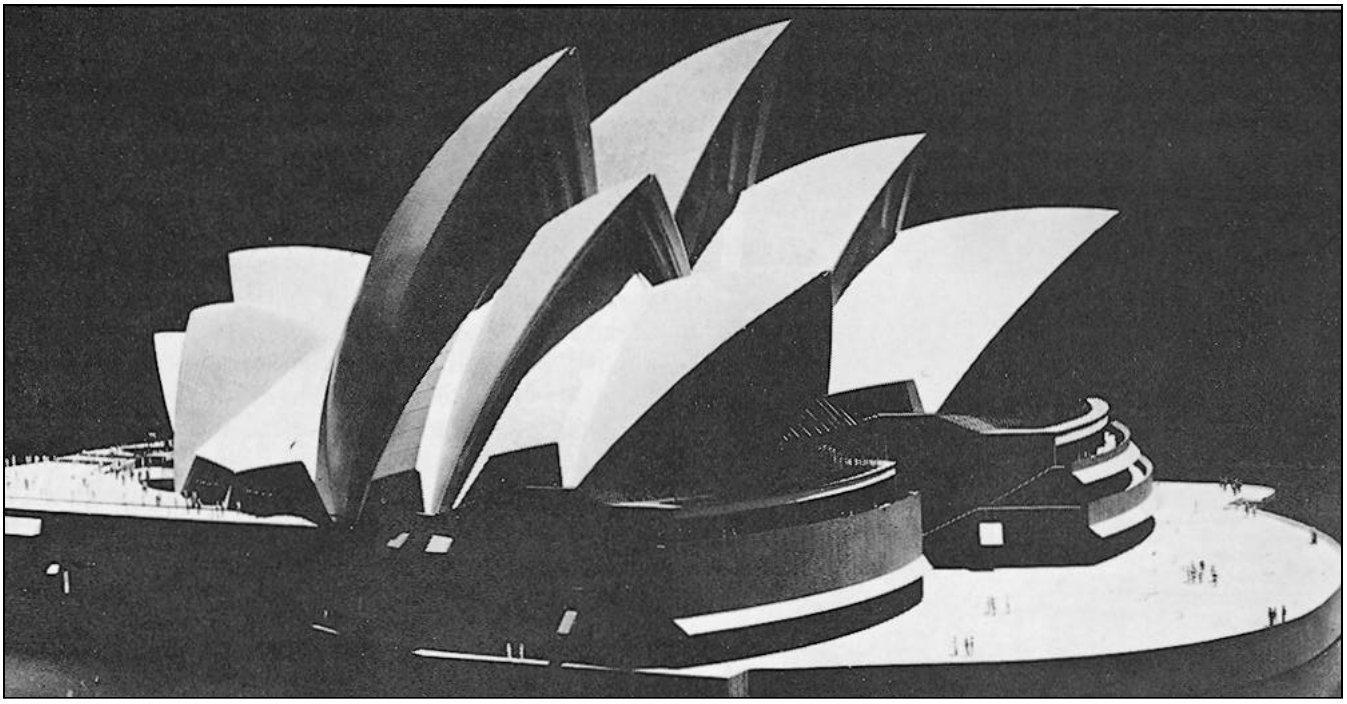


Sydney Opera House

. . . a symbolic design sketch grows into one of the world's most exciting buildings.

Constructions of Australia's "billowing sails" Opera House has followed an entirely unorthodox pattern. Designed by a young Danish architect, Jorn Utzon, the drawings were almost never submitted because he thought it would be useless. The assessing committee recognized the originality of the concept expressed, and also its perfect suitability for the site. The decision took a great deal of courage since the drawings included no details or even evidence of structural feasibility. It has been necessary at times to design the structure by experiment while building, and to invent techniques to solve problems that have never arisen before in the history of construction Originally the cost was estimated to be $8 million, but could rise to $100 million.

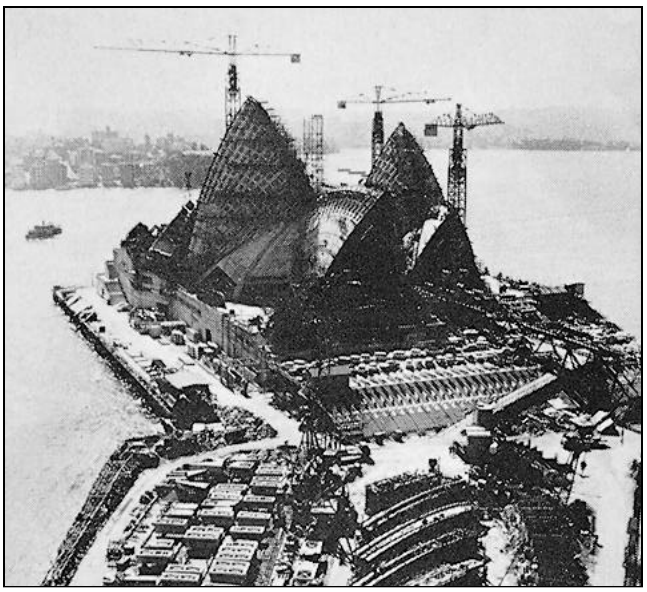
Construction was planned in three stages. Stage 1 covered the terraced base; Stage 2 is the shell construction still in progress; and Stage 3 will be the finishing and fitting operations. A large part of the building is supported on some 700 3-foot diameter, cased bored piers. The work was difficult because of tides. The presence of the sea water also meant that the whole structure below ground level had to be built as a number of waterproof reinforced-concrete compartments. The slab and steps of the concourse cover some 75,000 square feet with varying spans up to 164 feet. The slab is surfaced with 6 by 4-foot panels of artificial granite with open joints between them to carry away rainwater.

Without a computer the work would have been impossible. As the computer program got underway, Utzon's preliminary concept of free space curves had to be abandoned in the face of analysis and construction difficulties. It has proved possible to manipulate curves so that the tightness and grace of the original concept is retained, yet the fact that they are part of a single sphere cannot be detected.

At one point it was thought that all the shells could be constructed in the conventional way strengthened by ribs. This proved impossible and, as finally evolved, the roof is a totally precast, prestressed arched-rib structure. There are four main shells over each auditorium, the highest of which rises to 221 feet.

All the foundation columns for the shells are dissociated from the horizontal long-span slabs and walls of the base structure. They are arranged in units of four either side of the axes of the two main auditoria. Each unit is tied together transversely and longitudinally with post-tensioned connecting beams to restrain any tendency to movement under load. From the top of each column springs a site-cast arch pedestal and a shell pedestal. The arch pedestals provide the foundation for the side and louvered shells; the shell pedestals provide the foundation for the main shells. The main lift of the pedestals was 17 feet high and was placed non-stop. The pedestal forms were spherical, fan-shaped assemblies made up in panels of the same width as the arch ribs of the shells.

Erection and concreting of the shells is being carried



Construction of the "sails." Site precasting yards are seen in the foreground.

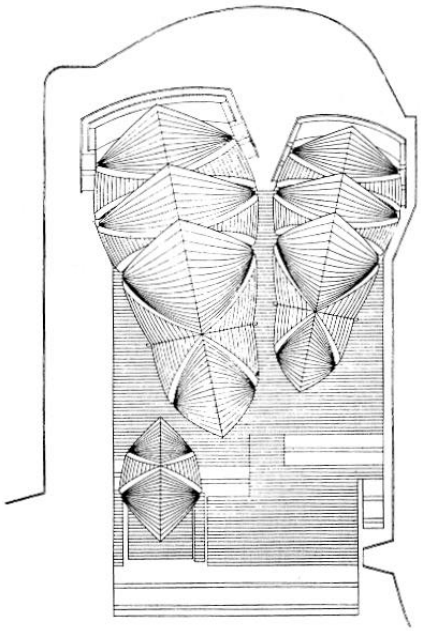
out with three 240-foot high tower cranes— the largest of their type in the world. The roofs are made up of some 2,500 precast segments, 15 feet long and varying in width from 1 to 7 feet. The segments weigh from 5 to 14 tons. They are placed on a movable, telescopic steel erection arch which is adjustable to match the geometry of the shell shape. Each rib of segments, as it is erected, is supported on the previous rib and on the movable arch, which moves forward as each rib is completed. There are up to 17 ribs in a shell; in the shortest ribs there are only 4 precast segments; in the longest rib there are 13 segments.

All the precast elements have been made at the site. They are cast in ten beds five elements long. Each element is cast on to the end of the previous one, the end surface of the one providing the end form for the next. Steel-framed plywood was used throughout as formwork. A very high quality finish is obtained by planing the plywood to a smooth finish and then coating it with a fiberglass-polyester resin laminate. A re-use rate for formwork of 30 to 40 times has been achieved. The concrete used is extremely dense; averaging about 155 pounds per cubic foot for the ribs. It is estimated that about 120,000 tons of concrete will be used in all for the project; the weight of the roof shells alone is 22,000 tons.

The side shells were erected first as follows: precast segments were located on top of each arch pedestal and stressed to it permanently. Further segments were then placed until the arches meet at the central plane of the shell between 70 and 150 feet above the tops of the foundation columns. When all four arches of a unit were completed and post-tensioned, a precast crown piece was inserted and site-cast in place. The arches are braced in pairs either side of the auditorium center-line by precast members that act as beam-columns. In addition there is a main brace between the arches parallel to the auditorium axis formed as a box beam. The side shells are finally clad with 2 1/2-inch thick site-precast slabs as an outer skin. Connections between the slabs and the beams and arches are site-cast to ensure rigidity.

The main shells are built out rib by rib, from the side shells. As the segments for a rib are positioned they are jointed with an epoxy resin to transfer shear and stressing loads. Temporary stress is then applied until all the segments are in place. When they are in place, permanent stress is applied through 21 stranded cables, 0.6 inch in diameter. The last step is to locate a precast keying ridge piece at the top of the arch to make the two halves continuous. The ridge piece is first positioned with a 3-inch concrete joint and then post-tensioned into the ribs by means of three cables. During erection each rib is allowed to deflect independently, until finally they are post-tensioned together laterally through thin site-cast joints. The prestressing operations at the site are very complex. In all, some 21,000 stressing and 10,000 de-stressing operations are involved as compared to say 1,500 and 2,000 operations for a major bridge.

The final stage of main shell construction is the fitting of external cladding in the form of some 4,000 spherical precast "lids" faced with a specially developed white ceramic tile—the "canvas" of the "sails." These lids which weigh up to 3 tons are also being precast on site; they are made of 3/4-inch thick ferrocrete, waterproofed and insulated. Some 1,400,000 tiles are needed. The lids are being bolted to the arch ribs.



Top view of Opera House showing location and positioning of shells.

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