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Roof Cladding of the Sydney Opera House

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Abstract: The tiled roof cladding of the Sydney Opera House is probably the most important visual element of the building. It has been designed and constructed within the constraints of a strong geometric discipline which dominates the form of the Opera House structure. The paper outlines the design development and details, methods of construction used, and the techniques which were evolved to construct these elements by employing factory production methods to take advantage of the repetitive geometric forms which make up the roof structure.

[Compiler's Note: So that this lengthy paper loads quickly, it is split between four separate web pages with links to previous or succeeding pages at top and bottom of each page. All illustrations are reproduced. Click on thumbnails to view figures and diagrams at full scale]

Introduction

Much has been written about the Sydney Opera House, and numerous books and papers have been published (see References). Some describe the more controversial aspects of this unusual building, whilst others deal with technical considerations. The building is extremely complex, and in a paper such as this it is possible to highlight only a particular aspect of the structure. The roof cladding or “tile lids”, as they came to be described during the construction, constitute the most important visual element of the building. The selection of the tiles, the way in which they were fabricated into large pre-cast components, the accuracy of manufacture and placing, as well as the intricate pattern formed by the arrangement of tiles on the lids introduces a strong sense of geometric unity which is the central theme of the whole of the roof structure and its cladding.

The Opera House is located on a peninsula jutting into Sydney Harbour on the northern end of the high-rise buildings in the central business area; it is adjacent to the harbour bridge and botanical gardens. It is a building which is seen in the round and from above—the sculptural form has been designed with this in mind and the selection of a material to cover that form was made by the Architect with great imagination and perceptiveness, producing a surface which expresses liveliness and interest under differing conditions of light—it is a form which is disciplined but never monotonous.

The Tiles

The tiles were manufactured in Höganas, Sweden, after extensive research by the Architect to achieve a white ceramic tile with glazed finish and an underlying rough texture. There are two types of finish, “matt” and “glazed” which have been arranged in a specific pattern on the lids—although a close scrutiny of the tiles shows a marked difference between the two materials, the

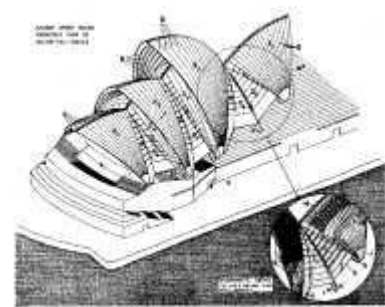
difference in reflectiveness creates a subtle pattern on the surface which defines the edges of the tile lids and introduces the underlying anatomy or structural form of the load-bearing elements beneath. Standard tiles are $4\frac{3}{4} \times 4\frac{3}{4}$ in (120x120mm) and $\frac{5}{8}$ in (10mm) thick—there are approximately 1,000,000 tiles cast on to 4,253 tile lids and eight different tile types. All tiles were cut to size in the factory before firing, packing and shipping from Sweden to Australia.

Tile Lids

In the original design submission, the Architect had expressed his intention to tile the roof, but the structure at that time was conceived as a cast *in situ* reinforced concrete shell comprising two thin concrete membranes separated by a cellular void. The geometry of the outer surface was defined by an elliptical paraboloid which was unsuitable for repetitive precasting. On such a surface, the tiles would have to be laid by traditional methods involving serious risk of tiles falling off due to thermal strain and inadequate bedding of individual tiles. It was inconceivable that this vast number of small tiles could be laid in a satisfactory manner by tilers working on the surface of the roof. This was an important consideration in the decision to change the geometric definition of the roof surface.

Geometry of the Roof Structure and Tile Lids

Figure 1. Isometric view of roof structure and cladding.



The roof structure covers the two main halls and the restaurant. There are three main elements forming each roof structure (Figure 1)—main shells (A1, A2, A3, A4), side shells (D5, D6, D7, D8) and louvre shells (C9, C10). Each shell is made up of two half-shells symmetrical about the central axis of the hall.

Each half is a mirror reflection of the others about a vertical plane along the central axis of the hall. Some leading dimensions give an indication of the scale of the roof structure. The height to the top of the largest shell from its springing point is 179 feet (54.6 m). The longest rib is made from 13 segments covered with 26 tile lids; the arc length measured along its centre line is 210 ft (64 m). Each half main shell (A1, A2, A3, A4) appears in elevation as a curvilinear triangle standing on a vertex. Each triangle which forms the outer surface of the shell is a portion of a sphere whose radius is 246 ft (75 m).

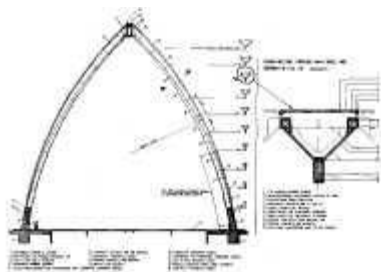
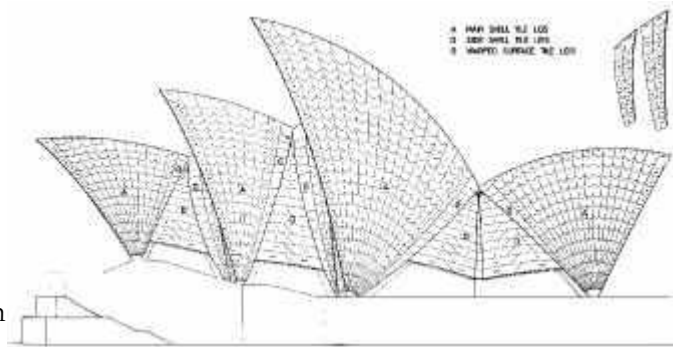


Figure 2. Diagrammatic section through shell showing detail of rib cross-section.

Each half main shell consists of a series of concrete ribs (B). The centre line of each rib is a great circle of the sphere. Centre lines are spaced 3.65° apart throughout each main shell. Each centre line passes through the pole of the sphere. In this way ribs and tile lids radiate from the podium

and become wider up the shell, successive ribs becoming longer or shorter as the case may be. The cross-section of each rib varies by smooth surfaces from a solid T to an open Y at the upper end (Figure 2). The ribs coalesce into a reinforced concrete pedestal (J) which provides a common spring point for all the main shell precast concrete segments. This arrangement of ribs and tile lids comprising similar elements forming part of a spherical geometry made it possible to develop a sensible construction process embodying the maximum use of repetitive elements.

Figure 3. Western elevation of Concert Hall showing arrangement of tile lids.



The louvre shells (C) are identical in principle to the main shells (A).

Side shells (D) are spherical triangles which link main and louvre shells—geometric derivation is shown in Figure 4. Here again each shell forms part of the surface of the same sphere. The “meridian” passes through the vertex of each shell; the boundaries of the side shells are small circles. Great circles intersect this meridian at right angles at 7 ft 6 in (2.28 m) intervals. Although each spherical triangle forming a side shell is different, the geometric principles are the same and hence fabricating elements of the side shell structure and tile lids could be planned on a repetitive basis.

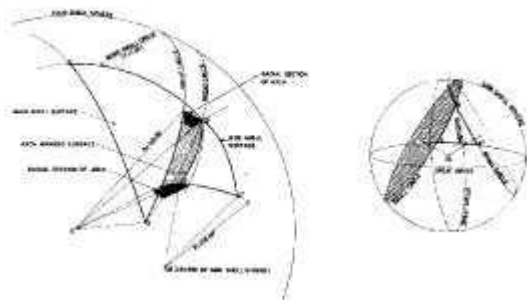


Figure 4. Geometric relationship between main shell, side shell and warped surface.

The space between the side shells and main shells is formed by a warped surface (G) described by two points which move up each shell boundary circle at the same rate and are joined by straight lines.

Cut Off Tile Lids

At the top of each shell the pattern of standard tile lids is terminated when the curved surface of the shell intersects a vertical plane parallel to the centre plane of each building. This introduced a special “cut-off” lid at the top of each rib. There are altogether 276 “cut off” lids on the main shells—the largest covers an area of 11 ft 6 in X 21 ft—although they follow the chevron form of the standard lids, each lid is different and it was necessary to set up two special forms for manufacturing these units. This involved work by skilled tradesmen, who set up the forms for casting each lid—a process generally not required in the tile yard.