The 8th Wonder of the World

By Wolfgang Toepfer

The Sydney Opera House celebrated its 20th anniversary in October 1993. Both from the point of view of architectural design and structural engineering, this building is the most conspicuous, the most complicated and the most improbable achievement in architecture of this century. The Sydney Opera House has become the symbol of modern Australia. More than one million people visit the building each year, and almost two million attend the performances.

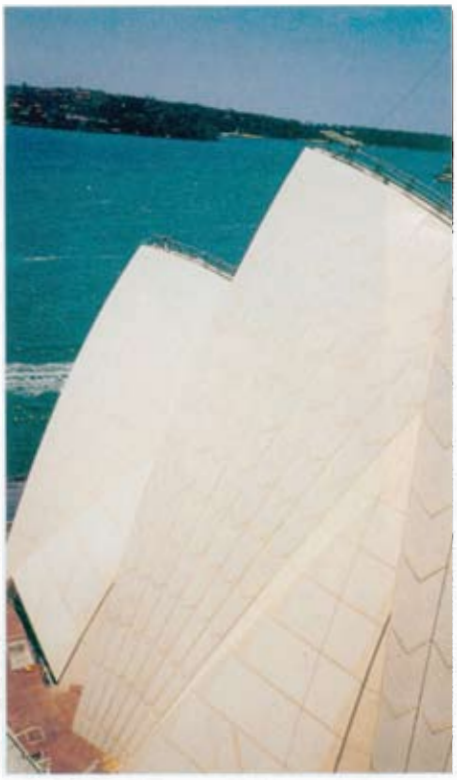
In the mid-fifties, the New South Wales government conducted a worldwide competition for the design of an "Arts Centre" to be situated at Bennelong Point, in the centre of Sydney's harbour. Jorn Utzon from Denmark won this competition with a design concept that was overwhelming but in no way complied with the prescribed conditions. Moreover, nobody knew how these wonderful shell-shaped roofs could ever be built.

During four long years of intense analytical work and countless model tests done primarily by the world famous Ove Arup engineering and consulting company, Utzon and Arup came up with a practical solution: the poetic shells were converted to a series of geometric shapes. The original design had to be changed somewhat but strictly applying the rules of spherical geometry did not diminish the sheer beauty of the roof design. The public, of course, has never been aware of any type of geometric discipline. People just rave about the wonderful "shells" or the "billowing sails".
The following article will mainly deal with the ceramic cladding material used on the roofs of the Sydney Opera House. The prefab tile panels were also manufactured exactly according to the underlying principles of spherical geometry. After some initial difficulties, the structural problems were under control and the tile-clad roofs were, in fact, completed as early as in 1967. They have now been protecting the interior of the building for 26 years, more than a quarter of a century of enormous daily changes in temperature, of continuous expansion and contraction of both the panels and the substructure, of extraordinary wind loads, of salty wind and acid rain.

When Jorn Utzon, the Danish architect who designed the Sydney Opera House, presented his audacious concept of the roof he knew already what he wanted to use as a cladding material: white glazed tile. The shell-like elements of the roof were supposed to be shiny and shimmering. Moreover, they were to be provided with a repetitive, geometrical pattern like the scales of a fish or the graphic design of certain shells. The roof surface was to be lively and changing under different conditions of light.

The only practical alternative to tile was concrete.

But after a few years, light coloured concrete slabs would become grey, tainted, with a high probability of patches of corrosion. After extensive research, Utzon decided on a white glazed extruded tile with a rough, textured surface. The white tiles were used as field tile. For trim and accent tiles, unglazed extruded tiles in a beige-cream shade were chosen.



The roofs are clad with 4.253 "Tile Lids" of different sizes

Surprisingly, the technical properties of tile did not play a very important part. In the mid-fifties the term "acid rain" didn't even exist. Utzon knew that the tiles he had picked were acid and alkali resistant and that they did not attract dirt, dust and oily substances. In fact, in the 26 years of their existence, the tiled roofs of the Sydney Opera House have never been cleaned mechanically, an outstanding achievement, also from the point of view of maintenance cost. The white shells are as glistening as ever!

Another danger that some people anticipated was the possible growth of fungi. Nothing of the sort has happened. In some areas the occasional growth of lichens has been observed but these lichens die back and cause only a minor visual intrusion.

The tile cladding of the roof of Sydney's Opera House is indeed self-cleansing and virtually maintenance free.

Originally, Utzon had thought that his reinforced concrete shell roofs could be cast in situ. The tiles were to be installed manually. Both these ideas - like many others that the genius had produced - did not work. The shell surfaces were elliptical paraboloids unsuitable for repetitive casting, and hand-set tiles would have been a much too risky solution because nobody could guarantee that the tiles wouldn't start falling off because of thermal strain effects or inadequate bedding.

The final solution provided for a rib-like substructure consisting of precast concrete segments. Onto this were fixed precast tile panels called "tile lids" by the Australian engineers that invented the system.

The structural, engineering and production problems were enormous. Several books have been written about these subjects.

The fact that the government had accepted Utzon's design without a cost estimate, detailed drawings or other relevant documents having been established, led to a construction period of 16 years and total cost of Australian $103 million which was approximately 15 times higher than the government's original estimate of $7 million.

Utzon resigned in 1966, 7 years after construction work had started. He had no answers to the technical problems. Australian architects took over the design of the functional spaces and the internal fitout of the building.

All in all, 4253 tile panels of various sizes had to be manufactured. The panels were made on the site. The maximum size of the main shell panels was 11ft. 6in. by 12ft. 6in., the maximum sizes of side shell panels and top shell panels were 7ft. 6in. by 30ft. and 11ft. 6in. by 21ft., respectively. The tile pattern finally chosen accentuated the chevron shape of the panels, with unglazed tiles being used on the outer edges.

The concrete forms for the tile panels were provided with an aluminium strip grid corresponding to the joint pattern desired. The tiles were placed face down in the mould, and animal glue was put on in order to partially cover the joints so as to prevent grout from penetrating on to the tile panel

A close-up of the remedial works which include replacement of 17 kilometers of sealant

surface. After that, three pre-cut layers of galvanised steel mesh were placed inside the mould, with spacers in between the mesh and the back of the tiles. The concrete mix for producing the panels was actually a sand/cement mortar that was compacted by a heavy float vibrator and by pencil vibrators. Finally, the surface was wood-trowelled. Steam curing followed 3 hours later.

The finished tile panels had a network of recessed joints. The heat from the steam melted the animal glue so that sharp re-entrant angles were formed between the cement mortar and the edges of the tile.

Special carriages allow two crews to inspect individual "Tile Lids"

Since there was some concern that this way water would collect and finally penetrate to the mesh reinforcements, all the recessed joints were sealed with a special epoxy compound.

After providing the back of the panels with a layer of insulation, the "tile lids" were hung up at the top on 2 aluminium bronze brackets. The lower end of each panel was left free to slide in a vertical direction in order to minimise thermal stresses in the panel. After having made the structure waterproof, the engineers decided to make the tile panels waterproof as well. To achieve this, the joints between the panels were filled with a PVC backing strip and a sealer called "Monolastomeric" - a two-part acrylic compound.

After about 15 years water leaks through the sealant developed with water emerging at the bottom of the outer shell. Except for one location water did not penetrate into the interior of the building. However, the leakage is of concern because corrosion of the tile panel reinforcement has already commenced where water has reached the unprotected underside of the "tile lids". In 1989 the New South Wales government decided on a 10 year upgrade programme amounting to $103 million (the sum that it cost originally to build the Sydney Opera House).

The largest contract in this programme is the replacement of 17 kilometers of sealants between the roof tile lids, an operation that will cost $6.5 million and will last two and a half years. All in all, 16 kilometers of sealant have to be replaced. Special carriages had to be developed to permit two crews to reach all the joints at every possible angle and in every corner. The new sealing material is an epoxy modified polyurethane.

Asked about the life expectancy of the Sydney Opera House, an official of the Public Works Department which is responsible for the entire repair and upgrading programme said: "the design life of the structure is 200 years. For the tiled roof it is 55 to 60 years". Almost half of this period is already over. Apart from minor details and isolated cases where a tile or two had to be replaced, there were no problems with the tiled surfaces. The cracks and the crazing that can be seen in quite a few of the tiles have been tested thoroughly for water and chloride penetration. The result of this test was that such defects do not represent a measurable risk. Debonding of tiles has mostly occurred where epoxy adhesive was used during original construction to replace damaged tiles.

The Sydney Opera House has been called ***"the most outstanding building of this century"*** or ***"the 8th Wonder of the World"***. Ceramic tile cladding is part of this wonder and still is the most conspicuous visual element of the building.

Formally a director and board member of Gail Inc., Wolfgang Toepfer, of Giessen, Germany, is now an international tile consultant specialising in market strategies, product and design concepts, market studies, international cooperation plans and reorganisation, as well as reconstruction jobs.

Details of the tiling and construction work

Field tiles: extruded white glazed tiles 120 x 120 mms, thickness 16 mms and extruded unglazed tiles, beige-cream 120 x 120 mms, thickness 16 mms

Trim: extruded unglazed tiles, beige-cream, 240 x 120 mms, thickness 25 mms

Special shapes: 8 different shapes cut to size at the factory

Total quantity: 1,056,000 pieces (approximately 14,000 sq mtrs)

Tile manufacturers: Hoganas, Sweden

Contractors: M.R. Hornibrook (N.S.W.) Pty Ltd (for the roof structure and the panels)

Architects and Civil Engineers:
Jorn Utzon
Ove Arup Partnership, London and Sydney
Hall, Todd and Littlemore, Sydney
Ted Farmer, N.S.W. Government Architect