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Sydney Opera House

Analysis and Cleaning of the Concrete

Paul Akhurst, Susan Macdonald and Trevor Waters

Abstract

This paper discusses the cleaning and conservation of the folded concrete beams, a key architectural feature of Sydney Opera House. This cleaning and conservation work attempts to develop an appropriate method and specific techniques for dealing with the exposed concrete that can be applied to other areas of the building in the future. It describes how the development of the methodology relies on a sound understanding of the historical development and construction of the building and the significance of the concrete in the architectural language of the place. It exemplifies the relationship between the Conservation Plan and the Utzon Design Principles that together provide the framework for decision-making at Sydney Opera House and shows these documents working in practice.

Through interviews with labourers, supervisors and engineers, consideration is given to site practices employed in 1964 that have proved to be stable and long-lasting. The development of the approach to the cleaning of the concrete also shows the value of combining oral and published history with laboratory assessment of conservation techniques.

Introduction

This is the second paper relating to the conservation of Sydney Opera House.¹ Previously the framework for the ongoing conservation and care of Sydney Opera House was described. This includes the implementation of a *Conservation Plan*,² together with the *Utzon Design Principles*,³ which jointly provide the guiding policy for the ongoing management of this important building. These policy documents have been adopted by the Sydney Opera House Trust as its managers, and are also used by the



Figure 1 Sydney Opera House was envisaged as a sculptural element in a magnificent harbour setting. It consists of a substantial, solid platform that draws on historic references. Atop the platform are the shells, constructed as segmented precast concrete ribs, overlaid with glittering white glazed tiles. (Courtesy Max Dupain & Associates)

government heritage agencies responsible for overseeing the conservation of the building.

The use of extremely high-quality exposed concrete at Sydney Opera House, cast *in situ* and incorporating precast elements, exploited the organic nature of the material – its colour intended to refer to nature. As Utzon said, ‘You find a similar situation in Gothic cathedrals, where the structure is also the architecture.’⁴ The top surface of the shells, in contrast, are covered with white glazed tiles, with the exposed structural precast concrete ribs forming the ceiling below (Figure 1).

The exposed concrete folding beams are a key feature of Sydney Opera House, providing the means by which the huge spans could be provided without columns, but also contributing to the architectural character and quality of the place. The building’s architect Jørn Utzon described the beams as ‘these ribs shaped so they elegantly express the forces within the structure. They express the harmony within the structure.’⁵

The folded beams support the southern part of the platform on which sit the soaring shells of Sydney Opera House. The beams rise from the ground, support the steps, and provide a concourse beneath. The folded beams also form the ceilings of the interior box office spaces, the preliminary foyers to the Opera Theatre and the Concert Hall, and the

ceilings of the grand external anteroom to these foyers – the Vehicular Concourse.

The *Conservation Plan* and the *Utzon Design Principles* both include detailed policies for the exposed concrete generally and the folded beams specifically, which are identified as being of ‘exceptional significance’.⁶ The work discussed in this paper includes cleaning and conservation of the folded exposed concrete beams that encase the Utzon Room and Vehicular Concourse below the monumental steps of the podium.

The recent concrete conservation and cleaning works to the Utzon Room and Vehicular Concourse required careful analysis and consideration. The importance of the aesthetics of the concrete finish in these areas demands that any conservation work recognizes this and that it reverses the effect of time and pollution on the finish of the concrete to preserve the material authenticity of the building and retard the environmental effects that contribute to concrete decay.

The study described in this paper attempts to address Sydney Opera House architect Jørn Utzon’s desire to ‘conceal the defects and bring it up to a uniform and acceptable standard’,⁷ and the *Conservation Plan*’s Policy 41.1 that ‘beams should remain unpainted and their detail unobscured’.⁸ Contemporary accounts and photographs highlight that the soffits of the folded concrete beams were blemished by a white residue when the formwork was removed in 1962, well before leaks through the protective membrane that sits above the folded beams became an issue. Thus the goal of determining what is ‘clean’ encompassed the removal of polluting agents and recapturing the visual continuity absent from much of the original surface. The initial investigation work described in this paper provides an overall philosophy and framework for the whole process of conservation from the initial consideration of the need for cleaning and conservation through to the completion of repairs and ongoing maintenance of the structure.

The folded concrete beams

Background

Jørn Utzon’s original competition drawings of 1956 show beams spanning the width of the lower concourse, which forms access for vehicular traffic and pedestrians into the podium (Figure 2).⁹ The folded beam profiles were arranged in a smooth flowing pattern, starting off as a ‘T’ section and gradually altering into an open ‘U’ profile where the tensile stress is concentrated in either the soffit or the crown. The geometry of the folded beams is a conic section in elevation,¹⁰ entirely created with straight lines in profile (Figure 3).

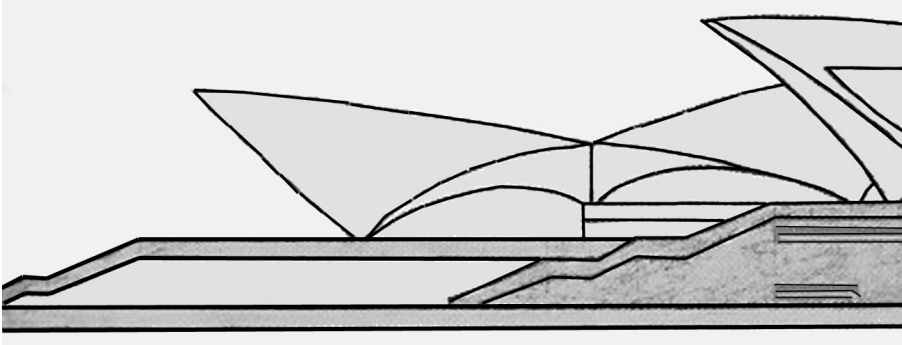


Figure 2 The supporting concrete beams span 47.5 metres (156 feet) across and down the slope of the grand stairs, without columns. The top surfaces of the structural beams are covered by precast granite paving, which incorporates open joints to let surface water run off into troughs formed between the beams. 'Submission no. 218', SOH Competition Drawings (Dec. 1956). Technical Information Management Services, Record No. D1419. (Courtesy of Sydney Opera House Trust)

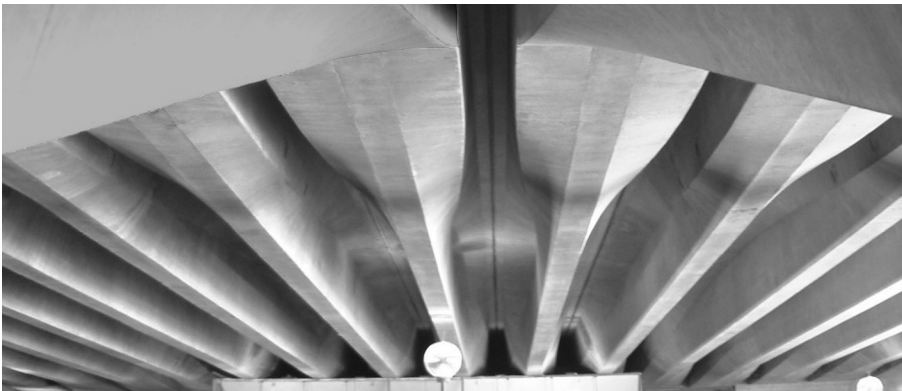


Figure 3 Detail of the folded beams. (Trevor Waters, 2004)

The construction of Sydney Opera House commenced on site on 5 May 1959. Late in 1960 the first pair of folded concrete beams was poured. Ove Arup and Partners were responsible for the design and construction supervision of the folded concrete beams. Despite the rigorous contractual requirements for the formwork, the beams did not achieve the smooth lines and sharp arises necessary to create the strong geometry that Utzon sought. The narrow formwork (Figures 4 and 5) precluded the efficient vibration of the concrete, particularly at the U-shaped knee. Excessive slurry escape had indicated formwork movement, whilst an obvious sagging at the knee indicated a fault in the supporting scaffold.¹¹ Despite efforts by the site supervisory staff to control the quality of the formwork,¹² the soffit of the folded slab acquired streak marks from the slurry escaping (Figures 6 and 7).¹³



Figure 4 Constructing the formwork for the folded beams. The sanding down of the grounds was insisted upon, thus weakening the 4 inch x 1 inch boards and so restricting the number of reuses, 1962. (Courtesy Max Dupain & Associates)



Figure 5 Large sheets of 3/16 inch plastic-faced plywood were used to line the formwork for the folded beams. Even minor damage involved the loss of the whole of that sheet, 1962. (Courtesy Max Dupain & Associates)



Figure 6 The special formwork called for by Ove Arup and Partners involved sinuous curves and elaborate setting out procedures for the soffits and beam sides. The tolerances demanded by the engineer were more consistent with precision joinery of cabinet making rather than formwork, 1962. (Courtesy Max Dupain & Associates)



Figure 7 This 1962 photograph shows the beams shortly after the formwork was stripped and reveals that the cleaning out of the forms was unsatisfactory. Excessive slurry escape in beams K1/K2 indicated formwork movement. The surface finish of the concrete was also unsatisfactory. (Courtesy Max Dupain & Associates)



Figure 8 The surface of the beams was burnished to create a uniformly white surface. (Trevor Waters, 2003)

The contractor developed a method of treating the freshly stripped concrete, in the northern foyers, to provide a more even finish. The concrete beams were rapidly dried with fan-forced heaters and slowly buffed with a sanding disc to disperse the surface efflorescence. The concrete was then burnished with coarse pads, on variable speed drills, to make the surface uniformly white (Figure 8).¹⁴ The quality of finish met with Utzon's approval, but he left Australia before treatment of a similar standard could be found for the hardened folded concrete beams.

The 2002 *Utzon Design Principles*, which specifically mentions the concrete finish, confirms that a cleaning and resurfacing process is still necessary which is reversible and does not obscure the texture of the concrete.^{15,16}

Some form of treatment of these surfaces as a whole, or in part will be necessary to conceal the defects and bring it up to a uniform and acceptable standard. Such a standard has now been set by the quality produced in the shell structure and most recently in the bar areas, but the actual treatment will depend on the outcome of experimental work ...

Defining an approach to cleaning of the exposed concrete finishes

The condition of the folded beams has deteriorated through prolonged penetration due to membrane failure¹⁷ and the common practice of direct fixing to the beam structure, as well as *ad hoc* service penetrations. As required by the *Conservation Plan* and identified in its policies,¹⁸ careful investigation and analysis of the surface was undertaken. The intention of

this approach was to avoid further deterioration and to develop potential conservation treatments that would be stable and durable over time. Cleaning treatments should remove contaminating matter as well as even out the mottled concrete substrate that Utzon regarded as defective and detrimental to the intended character of the original surface.

The *Conservation Plan* contains a number of detailed policies about the exposed concrete beams. These include policy on surface finish (colour and texture), the importance of using tried and tested methods and proper diagnosis of problems, technical adequacy of repairs, and the retention of construction markings or characteristics. Likewise, the *Utzon Design Principles* also addresses the concrete finish in terms of colour and texture.¹⁹

The goal of the cleaning process is to rectify obvious defects and also to establish the appropriate methodology and techniques for the cleaning and conservation of other sensitive areas of off-form concrete ceilings within Sydney Opera House.²⁰ The objective of the cleaning process for the folded concrete beams is to:

- 1 remove or reduce pollutants from the fabric whilst retaining the natural visual properties of the concrete surface;
- 2 treat the unpainted concrete soffits to even out blemishes and to recapture their early visual appearance in texture, colour, tone, and uniformity;²¹
- 3 ensure that the cleaning procedure above is only executed through processes that are fully tested on the actual fabric and for which the consequences are known, and not to introduce agents that may result in future visual change or deterioration;
- 4 retain the original post-tension set-out lines, vibrator markings, and patches that help to explain the past history of the fabric; and
- 5 involve processes that are stable, long-lasting, and as simple in application as the complexity of the task permits.²²

Field survey and testing

Prior to commencement, a photographic record of the areas to be cleaned was developed, with the images compiled to provide detailed mapping of the cracks and water ingress. Stress cracks radiating from the anchorages that occurred during construction were identified from the resident engineer's records (Figure 9).²³

Some water staining had occurred along the cracks, which suggested that the membrane covering the slab had failed. There was evidence of water ingress. Leaching was noted at a crack in the knee and a scraping was taken. Preliminary analysis indicated that the material is likely to be

calcium carbonate with low levels of sulphate. Further scrapings were taken for laboratory analysis to determine the nature and source of the blemishes.

Three concrete core samples were analysed to determine chloride and sulphate penetration profiles at different depths below the surface of the concrete. At selected depth intervals, layers were ground in a laboratory disc mill to less than 1 mm and analysis was performed.

Table 1 and Table 2 illustrate that with the exception of some results from the outer layers, the chlorides were well below the 1150 ppm (0.4 per cent by weight of cement) threshold of concern,²⁴ and would not constitute



Figure 9 A photographic survey of the folded slab to the Utzon Room mapped the open crack and areas of water ingress. The arrows highlight the crack and leaching of the beam as a result of water penetration. (Trevor Waters, 2004)

Depth (mm)	Chloride (ppm)	Sulphate (ppm)
All	100	110
0–10	100	1,020
20–30	70	770
40–50	50	790

Table 1 Chloride and sulphate concentrations at depths up to 50 mm within the Utzon Room.

Depth (mm)	Chloride (ppm)	Sulphate (ppm)
All	580	2,050
0–10	770	420
20–30	130	340
40–50	<10	450
140–150	10	330
160–170	<10	360
180–190	20	910

Table 2 Chloride and sulphate concentrations at 190 mm depth within the Vehicular Concourse.

a significant risk of chloride-induced corrosion of the reinforcing steel with cover greater than 20 mm. It also appears that the original mix of concrete had a very low chloride content, in the order of 20 ppm. While the absolute levels of sulphates detected remained well below the threshold (14,000 ppm or 5 per cent by weight of cement), these results indicate some elevation of sulphates above the background.²⁵

Prolonged exposure to the sulphates and chlorides in sea spray may have promoted the development of insoluble calcium sulphate dihydrate (gypsum) and calcium chloride to the top and lower surface of the beams in the Vehicular Concourse areas. There is no evidence of salt penetration through the concrete, or of internal seawater attack.

Surface scrapings of the folded concrete beams were collected from different locations within the Utzon Room to determine the composition of the stains and blemishes to the soffits.²⁶ The laboratory results are graphically represented as a percentage by weight of calcium carbonate CaCO_3 , calcium hydroxide Ca(OH)_2 , hydration water H_2O , organics, and quartz (or other) (Tables 3 and 4).²⁷

Thermal analysis of the concrete surface scraping samples reveals a greater proportion of mineral deposits than of organic matter such as

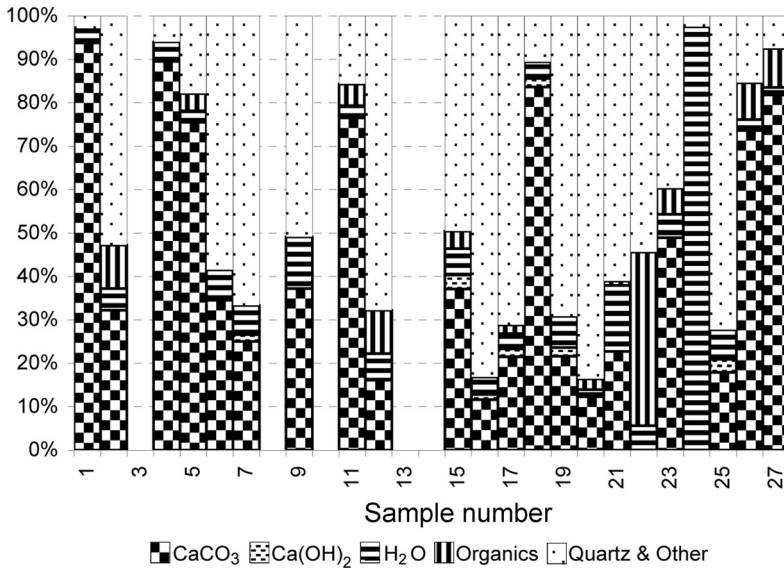


Table 3 Analysis of surface scrapings.

CaCO ₃	Ca(OH) ₂	H ₂ O	Organics	Quartz and other
41.50%	0.67%	9.58%	4.64%	43.61%

Table 4 Scrapings average % composition.

algae, fungi, bacteria, smoke residue, or formwork oil. This type of organic deposit is more likely on the exposed beams at the extremities of the Vehicular Concourse. Here the weathered and porous surface presents an ideal habitat for organic growth to establish.

Notable quantities of calcium hydroxide $\text{Ca}(\text{OH})_2$ were detected in samples collected from active water leaks. Samples 15 to 19 were taken from areas with distinct white efflorescence close to construction joints or cracks with a stream of deposits on the soffit. The weeping of lime is usually caused by acidic rainwater (carbonic acid) dissolving calcium from the cement matrix to form calcium bicarbonate $\text{Ca}(\text{HCO}_3)_2$. Precipitating calcium salts form as a bloom or indistinct whitening around the leak.²⁸

The ratio of CaCO_3 to quartz over the soffit of the concrete is variable. However, there is no evidence of significant leaching of concrete components and subsequent salt deposition on the soffit of the beams. The variable coloration is due to the uneven distribution of calcium hydroxide $\text{Ca}(\text{OH})_2$. This is a natural by-product of the hydration of cement that has carbonated on exposure to air forming insoluble calcium carbonate CaCO_3 . This chalky residue is the most likely cause of the 'cloudiness' in the matrix of the concrete and streaks, clearly described by the resident architect and evident in the contemporary photographs taken during construction (See Figure 7).

Further chemical analysis of surface scrapings was undertaken to determine if there was a compositional variation between the staining in the exposed Vehicular Concourse and the interior of the Utzon Room (Tables 5 and 6).²⁹ The expected outcome was that due to the failure of the original membrane there would be evidence of external seawater attack and salt penetration in both areas sampled.

Sample 1A is taken from the level portion of the beam adjacent to the south-eastern wall of the Utzon Room. Serious leaking of water through the open crack has led to the formation of stalactites on the soffit of the folded beam. There is evident failure of the original and new membranes.

The scraping was taken from this fissure and analysis has proved it to contain predominantly calcium salts (5.3 per cent). This is symptomatic of a significant rainwater leak. The results show the composition of magnesium oxides to be very low, less than 0.5 per cent, with a small percentage of both sodium and potassium oxides. These low concentrations do not indicate a more severe problem of saltwater migration that is having an adverse effect on the concrete durability. Few sulphates were detected (0.03 per cent) and the cement surrounding the crack does not have the friable material that would be expected if the crack was caused by the softening or dissolution of the hydrated cement by sulphate present in seawater. Furthermore the low levels of iron oxide suggest that rusting of the reinforcement by water ingress may not be widespread.

	Sample 1A Utzon Room	Sample 5A Vehicular concourse
Raw element analysis results (% by weight)		
%Fe	0.2	2.9
%Ca	3.8	2.6
%Mg	0.1	1.2
%Na	0.8	0.9
%K	0.8	1.0
%SO ₃	0.03	5.7
%Cr	n.d	n.d
Recalculated oxide composition (% by weight)		
%Fe ₂ O ₃	0.3	4.1
%CaO	5.3	3.6
%MgO	0.2	2.0
%Na ₂ O	1.1	1.2
%K ₂ O	1.0	1.2
%SO ₃	0.03	5.7
%Cr	n.d	n.d
Oxide Σ	7.8	17.9

Table 5 Chemical analysis of surface scrapings.

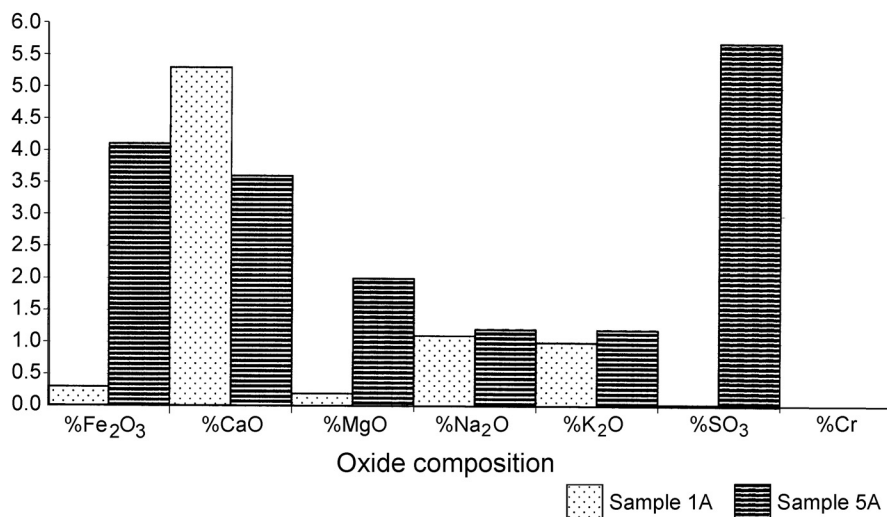


Table 6 Graph of the recalculated oxide composition (% by weight) for the Utzon Room (Sample 1A) and the Vehicular Concourse (Sample 5A).



Figure 10 The folded concrete beams to the Utzon Room retain the original mottled and rust-stained finish that was evident in 1962 construction photographs. (Trevor Waters, 2003)

Sample 5A was collected from the sloping soffit of the western beam in the Vehicular Concourse. Although the internal concentration of sulphates was low, the superficial build-up of SO_3 (5.7 per cent by weight) is a concern. Unless sulphates being deposited by sea spray are regularly cleaned off, there is a risk that they will attack the cement matrix and induce corrosion of the reinforcing steel. Very slight sulphate attack has been detected on the external faces of the first and last beams, which are those closest to the harbour.

The 4 per cent iron oxide component is consistent with an overall rust coloration within the Vehicular Concourse and is probably a stain from construction. The formwork was exposed for long periods, largely due to the extra quantity and complexity of reinforcement, causing excessive weathering deterioration. The increased reinforcement made it difficult to clean out the forms before casting.³⁰ Rust from the bars was washed onto the soffit formwork by rain, resulting in the permanent staining of the concrete face (Figure 10).

The preceding test results support the view that the concrete is sound, of high strength and relatively impervious to moisture. Furthermore the permeability of this high grade of concrete would not allow a ready migration of salt except through obvious cracks.³¹ The analysis of cores and surface scrapings has demonstrated that the current efflorescence and staining was present, in part, when the slabs were first poured. The discontinuous and uneven surface that so displeased Utzon in 1962 is integral to the structure and is not the result of salt penetrating through the folded concrete beams and depositing on the surface.

Conservation programme

As recently as 2002 Utzon continued to express his dissatisfaction with the presentation and finish of the folded concrete beams to the Vehicular Concourse, Utzon Room, and southern foyers:³²

One way to remedy this is to raise the light level in the area artificially. Another way could be to whitewash the concrete surfaces of the ceiling above the area. Whitewash can be cleaned off again, or applied in such a way that it does not camouflage the concrete texture. Trials in 'selected' areas would be needed to establish the correct procedure.

Steve Tsoukalas, conservation tradesperson, has worked on the construction and maintenance of Sydney Opera House for thirty-five years. He retained the tools necessary for the original finishing process and was able to demonstrate the original buffing process that turned dull, blotched concrete into a lustrous, translucent finish (Figure 11). On freshly stripped concrete the cleaning process is similar to the process employed in the buffing of the northern foyer beams after 1964. The surface staining, rust streaks, and calcium hydroxide $\text{Ca}(\text{OH})_2$ blemishes are dispersed evenly with a coarse pad on a 7-inch variable-speed buffing tool. The precipitate is worked to a constant edge in a tracking motion rather than broad uneven strokes, taking care not to leave behind swirl marks or a slurry build. The pressure is gentle and the speed is slow (400 rpm). As the calcium hydroxide is buffed the slurry becomes a tacky or viscous film on the surface. Within a month the surface is fully carbonated to a translucent

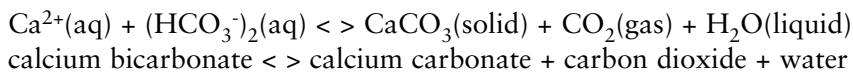


Figure 11 Steve Tsoukalas demonstrates the use of the original drill used to burnish the soffits of the freshly stripped concrete. The hardened concrete is currently 'reactivated' with a calcium bicarbonate solution that evens out the blemishes and fills the pores, creating a denser surface. This figure demonstrates the process only – correct safety procedures were followed when undertaking the task. (Trevor Waters, 2003)

calcium carbonate film that has a strong polarizing effect when viewed through a polarizing film. This is typical of calcite crystal formation.³³ The same tools and action were initially unsuccessful when used for the conservation treatment of hardened concrete. Site trials demonstrated that once the calcium hydroxide (lime) had fully carbonated on the folded concrete beams, the resultant calcium carbonate (calcite) was difficult to remove. As calcium carbonate is virtually insoluble and has little binding power it is important that it is dissolved and dispersed evenly into the micropores of the concrete. An emulsion was required that would significantly increase the solubility of calcium carbonate in water. Laboratory experiments and site trials investigated lime washes and thick calcium carbonate suspensions that were 'painted' over the surface, but obscured the character of the concrete. Sugar solutions readily formed soluble calcium saccharate; however, analysis confirmed that even after repeated washing residual sugar formed loose organic bonds with hydroxides, reducing alkalinity and increasing the risk of degradation. Sodium silicate, which reacts with free hydroxides to form a glass-like binder around the calcium carbonate, was also considered.³⁴ These treatments were rejected as they did not fulfil the primary objective of involving processes that are stable, long-lasting, and simple in application.

Conservation treatment

The treatment adopted follows the same process that enables acidic rain-water to dissolve calcium carbonate from within cracks and disperse it evenly over the soffits of the beams. Thus the hardest problem, water ingress, becomes the basis of the simplest solution. The mixture is easily prepared by dissipating calcium carbonate in a bottle of carbonated water. This carbonic acid H_2CO_3 dissolves the insoluble CaCO_3 into the soluble calcium bicarbonate $\text{Ca}(\text{HCO}_3)_2$.



The soluble 'life' of the bicarbonate is limited. If the container is left open CO_2 gas is desorbed and CaCO_3 precipitates from solution; the same effect is obtained at drying. This process when applied to cleaning hardened concrete has the potential to induce controlled dissipation.

The substrate is first steam-cleaned to remove organic deposits and soluble salts, leaving the micropores more open. The substrate is left to dry for several hours so that it will absorb the carbonated water faster and deeper. A fresh bicarbonate solution (prepared just before application) is applied as a thin wash over the surface of the concrete. The depth to which

the calcium bicarbonate will penetrate depends on factors such as opened porosity or moisture content.

Once the calcium bicarbonate is applied and absorbed into the pores of the concrete, the subsequent evaporation of the water will generate precipitation of the calcium carbonate into the pores. Slow, natural evaporation is preferable to accelerated drying. Gentle buffing with a coarse finishing pad, during drying, changes the surface from a translucent film to a tacky opaque glaze. This is the same effect as observed on freshly stripped concrete. When it is dry a microscopic layer of calcium carbonate is formed on the surface and within the pores of the concrete. This treatment evens out the dappled blotches, disperses the rust stains, lightens the surface, and recaptures the character of the concrete beams as they appeared after removal of the formwork (Figure 12).

Consequently, Sydney Opera House has adopted a low-pressure cleaning solution saturated with calcium and containing an excess of dissolved CO_2 . Carbon dioxide is bubbled through a suspension of water and calcium carbonate to form an acidic calcium bicarbonate solution (6.75 pH at 11°C and 140 psi). Calcium solids are initially dissolved from the surface of the concrete and then evenly deposited as the water evaporates and carbon dioxide is lost from the liquid. In practice the bicarbonate solution removes superficial grime and efflorescence, evening out the white staining (Figure 13).

Although some carbonation of the existing calcium hydroxides within the concrete can be considered to be occurring, this process can be regarded as a way of introducing carbonation from external sources, causing the calcium carbonate to be formed on the surface, not within the concrete matrix.³⁵ The depth of full carbonation remains less than 1 mm before and after cleaning.

Conclusions

The conclusions to be drawn from the development of a methodology for the cleaning of the concrete and conservation of the surface finishes of the concrete at Sydney Opera House are two-fold. First, the cause and treatment of surface discoloration has been comprehensively established. Second, through detailed historic understanding of the building as well as sound scientific investigation and a robust philosophical approach, an approach to maintenance has been demonstrated that can be transferred to many situations and materials.

Sydney Opera House has undertaken extensive investigations regarding the causes of discoloration of the folded concrete beams. These have demonstrated that the efflorescence and staining were present, in part, when the slabs were first poured. The variable coloration is due to the



Figure 12 The Utzon Room presentation has been improved by the cleaning and treatment of the concrete without compromising the character of the concrete finish or having to remove early structural patches that help to tell the story of the place. The work sought to reinstate the authentic finish of the exposed concrete, which is such a strong aesthetic element in the building. (Trevor Waters, 2005)



Figure 13 Visual inspection of the soffits confirmed that there were no apparent adverse effects from the cleaning process. (Trevor Waters, 2005)

uneven distribution of calcium hydroxide $\text{Ca}(\text{OH})_2$. This is clearly evident in the contemporary photographs taken during construction. Treatment with calcium bicarbonate has successfully evened out the discoloration and brought the beams closer to the architect's original intent. The effect of the cleaning and treatment is to remove sulphates, soiling, and stains, whilst not altering the character of the off-form finish.

The approach taken to developing this treatment is consistent with the unique original design and construction process at Sydney Opera House: that is investigation, experimentation, and implementation. Experimentation on any significant fabric must be undertaken with great care so as not to cause irreparable damage. Through investigation the architect's original intent was established (*Utzon Design Principles*), whilst the conservation management plan provided practical policies for evaluating the heritage significance of the elements to be treated in a current context. Records from the design and construction period further informed the maintenance process. By augmenting documentary records with the collective memory of former workers and supervisors, it was possible to reproduce the techniques employed after 1964. This philosophical approach, adopting considerable investigation before undertaking any work or even experimentation, can be readily applied in many situations and demonstrates the value of understanding the designer's intent before commencing restoration work. This is important when the significance of the place is largely derived from the architectural significance, as is the case at the Sydney Opera House.

This work provides an important record and template for the treatment of the exposed concrete of Sydney Opera House that can be used in the future. By example, this work establishes a documented approach to maintenance and restoration based upon scientific principles and an understanding of the intent and achievements of the original architect and construction workers.

Biography

Susan Macdonald BSc(Arch), BArch, MA(Conservation Studies), RIBA

Susan trained as an architect in Australia before spending ten years in London. A former secretary of DOCOMOMO UK and committee member of Australia ICOMOS, she has a particular interest in the conservation of twentieth-century places and has written three books on this subject. Susan is currently the Assistant Director at the NSW Heritage Office in Australia.

Paul Akhurst BSc(Hons), MSc(Cantab)

Paul has degrees in building management and interdisciplinary design for the built environment, and has previously published on change management. He has spent most of the past twenty years working in the UK and Australian construction and facilities management industries. Paul is currently the Director of Facilities at Sydney Opera House.

Trevor Waters BArch

Trevor is one of the few heritage architects in New South Wales employed as a builder rather than a professional consultant. He has worked in this capacity on a number of important projects in New South Wales including St Mary's Cathedral. Trevor developed the method for cleaning the concrete and supervised the site trials and the execution of treatment of the folded concrete slabs at the Sydney Opera House.

Notes

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- 2 Kerr, J. S., *Sydney Opera House: A Plan for the Conservation of the Sydney Opera House and its Site* (3rd edn.), Sydney Opera House Trust (SOHT), Sydney (2003), p. 36. Available at http://sydneyoperahouse.com/sections/corporate/about_us/pdfs/aboutus_conservationplan2003.pdf accessed 28 September 2005. This document, which has been formally adopted by the Sydney Opera House Trust, outlines the history and significance of the building and its elements and provides comprehensive policies for its care and conservation.
- 3 SOHT, *Sydney Opera House Utzon Design Principles*, SOHT, Sydney (2002), p.53. Available at http://sydneyoperahouse.com/sections/corporate/about_us/pdfs/aboutus_utzon_design_principles.pdf accessed 28 September 2005. This document, written by Jørn Utzon, the building's architect, provides design principles that can be used as a reference for the conservation and evolution of the building. These principles provide a first-hand account of the design drivers or intent that underlay the place.
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- 5 Ibid., p. 25.
- 6 Kerr, *op. cit.* (2003), p. 36.
- 7 SOHT, *op. cit.*, p. 53.
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- 24 Australian Standard HB84:1996, *Guides to Concrete Repair and Protection*, Section 2.22.3, Fig 2.2.
- 25 Salome, F., Director, CTI Consultants Pty Ltd., 'Chloride and Sulphate Content of Cement, Opera House', CTI Job: 1443 (27 Feb. 2004), p. 4.
- 26 Simultaneous differential thermal and thermal-gravimetric analysis (DTA-TGA) was conducted. Of the 31 scrapings collected, 22 samples were of sufficient size to be analysed using a TA Q600 instrument.
- 27 Paraschiv, V., Senior Development Engineer, Australian Construction Materials, File 627/04 (July 2003).
- 28 Experimental observations and computer modelling have shown that rainwater or seawater flows also precipitate calcium within the porous system and under certain circumstances the calcium carbonate, with low solubility (0.0013g/100g @ 25°C), may fill the crack, preventing further leaks. (Brodersen, K., *CRACK2 – Modeling Calcium Carbonate Deposition from Bicarbonate Solution in Cracks in Concrete*, Risø National Laboratory, Roskilde, March 2003.) High concentrations of CaCO₃ were detected in samples 1 to 5 collected from fractures or cracks with no evidence of moisture. This is in all probability the result of this crack-filling phenomenon.
- 29 Paraschiv, V., *op. cit.*
- 30 Nicklin, M. S., 'Sydney Opera House, Stage 1, Arbitration on Folded Slab Formwork', (Nov., 1962) p. 3.
- 31 Morehead, D., Arup Façade Engineers, 'Folded Concrete Beam Investigation' (Sept. 2003), p. 3.
- 32 SOHT, *op. cit.*, p. 26.
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- 35 The introduced carbon dioxide could be increasing the depth of carbonation of the concrete, reducing its alkalinity and making the steel reinforcement more vulnerable to corrosion. In practice the calcium carbonate formation appears to be superficial only and the depth to which the alkalinity has dropped below 9.2 pH within the concrete matrix is unchanged.