Concrete Conservation

Sydney Opera House
Concrete Conservation Project
Final Report Summary

August 2018

Contents

Sydney Opera House is World Heritage listed as a masterpiece of human creative genius. It is a pioneering example of the use of concrete in 20th century architecture.

Jørn Utzon's crowning architectural achievement has also become the symbol of modern Australia, the nation's premier tourism destination and one of the world's busiest performing arts centres. The site welcomes more than 8.2 million visitors and hosts more than 2,000 performances attended by 1.5 million people each year.

It is vital that we treasure and renew this remarkable place for future generations, and ensure it continues to welcome and inspire people in as many ways as possible.

A critical part of our custodianship will be the conservation of the building itself. The Opera House, famous for its innovative use of exposed structural concrete, has been subjected to the elements for more than 50 years. While the concrete is in very good condition, we must do everything possible to keep it that way. The challenge is to find the most effective way to monitor the concrete's condition and to develop best-practice strategies for its long-term conservation.

This is why the Getty Foundation's grant is so significant. It has enabled an intensely productive partnership between the Opera House, the University of Sydney and Arup. This collaboration has produced a robust, logical, repeatable and auditable system for inspecting and testing the concrete, so that we can take early actions to conserve it.

The impressive result is a Concrete Conservation Framework that is underpinned by the heritage policies established in our Conservation Management Plan (4th Edition) and the visionary Utzon Design Principles, and fully integrated with our new Building Information Management Model as it develops.

Through this work, we have learned a great deal about the building and the task before us to safeguard its fabric. We hope those lessons will be useful for many other culturally significant modern buildings around the world.

I would like to thank the Getty Foundation, faculty and students of the University of Sydney and our long-standing partners Arup, as well as all the members of the Opera House project team. The expert guidance provided by Sydney Opera House Conservation Council members Sheridan Burke and Dr John Nutt AM (now retired) on the project steering committee is also greatly appreciated. Finally, my gratitude goes to the original Opera House construction workers, some of whom have provided us with vital oral histories that will inform our conservation efforts well into the future.

It is wonderful to see the spirit of creativity, innovation and collaboration that produced the Opera House being applied to its conservation.

Louise Herron AM
Chief Executive Officer

INTRODUCTION

Concrete Conservation Project

Sydney Opera House is a major concrete building, widely regarded as one of the greatest buildings of the 20th century. Built between 1959 and 1973, with a design life of 250-300 years, the structure is still in the early part of its expected life.

After more than 50 years exposed to a marine environment and the impacts of millions of visitors, some specific areas of risk in the concrete re being monitored through a robust preventative and corrective maintenance program. It is timely to undertake closer analysis of the condition of the steel-reinforced concrete in the structure to ensure its longevity.

In 2014, the Opera House successfully applied for a grant from the Getty Foundation to examine the concrete in three high priority areas. These areas were selected, in consultation with expert advisors, due to their critical function in the building structure, their visual prominence, and the risks from marine exposure and impacts of potential water ingress.

ROOF SAILS

The most recognisable part of the Opera House building, the sails are fully exposed to the marine environment, and could be vulnerable to water ingress should there be any failure in the ceramic tile skin, or in the grouting inside the post-tensioning ducts of the ribs. Regular inspections of accessible areas indicate that the condition of the protective system is good, however the Opera House is searching for new non-destructive testing methodologies that will enable the condition of the inaccessible interior of the sail structures to be monitored.

ROOF PEDESTALS

These steel-reinforced concrete structures at the base of the roof sails are completely exposed to the natural elements and to human touch. There is a particular impact from rainwater runoff, which causes erosion and biological growth on the structures. Protective coatings have been trialled in the past, and all have been rejected due to either being ineffective, or having an unacceptable architectural impact.

UNDER THE BROADWALKS

The Broadwalks are built on steel-reinforced concrete piles, which stand in the Harbour. The Western Broadwalk is fitted with cathodic protection, while the Northern and Eastern Broadwalks are not. The project studied the condition of the concrete under the Northern Broadwalk.

There's a wealth of knowledge contained in numerous studies and reports that had been completed in the past but there was no single point of information storage. The reports needed to be located, analysed and collected into an integrated database.

The Opera House was keen to engage with academics in the study of the building structure and its conservation, and wanted to identify and classify the concrete assets into a strategic framework.

With the funding from the Getty Foundation, which the Opera House matched, an academic partnership was sought out. The University of Sydney, offering engineering and architectural conservation courses, fit the project's objectives.

The University of Sydney agreed to enlist students to complete six thesis studies to locate and analyse previous reports on the Opera House concrete, and to develop non-destructive testing methodologies to assist in monitoring the condition of the structure. The Opera House required that all ideas were fully developed and tested in a laboratory setting before being applied to the Opera House building.

An expert steering committee was established, comprising Sydney Opera House Conservation Council members, University of Sydney, Arup structural engineers, and Opera House management, which met monthly to guide the project.

The project was established in three parts:

CRITICAL ANALYSIS

Twelve students from the University of Sydney undertook six areas of study, aimed at locating and analysing previous studies completed on the Opera House concrete.

NON-DESTRUCTIVE TESTING

Students, faculty and industry professionals were tasked with applying established, new and emerging technologies to develop non-destructive testing methodologies capable of providing a better view inside the concrete structures of the Opera House.

DEVELOPMENT OF A CONCRETE CONSERVATION FRAMEWORK

The Concrete Conservation Framework consolidates the long-term condition monitoring, preventative and corrective maintenance programs for the Opera House's concrete. The framework will produce an interactive system connecting condition monitoring in the field with the developing Building Information Model.

As a result of the project, the critical analysis was completed and an organised database of existing research was established in the Repository of Knowledge. This information was greatly expanded through oral history research, which was completed with several experts who had worked on construction of the Opera House, or on key maintenance projects since the building opened.

Since the project was completed, these experts have continued to participate in the formation of the Concrete Conservation Consultation Group, which meets with Opera House management twice a year to continue progress on concrete conservation.

The project team's goal was to devise a Concrete Conservation Framework that could capture regular condition monitoring in the field and assist Opera House management in identifying potential risks, including the capability for predictive modelling. A parallel project to develop the synergy between our Building Information Model and Facilities Management capability has helped further this goal.

The project continues to evolve with emerging technology. Appendix A describes the Opera House's proposed concrete classification system, and outlines the system currently in development to link field inspections with the Building Information Model.

How to read this book

This report provides details of each aspect of the Concrete Conservation Project, as well as updated information on progress made since the conclusion of the Getty funded project in mid-2016.

This book is divided into the following Chapters:

CHAPTER ONE

An overview of the Opera House's significance, history, design and conservation management. This chapter provides contextual information to assist in understanding some of the background story of the Opera House, and how the structure was built.

CHAPTER TWO

Details of the Concrete Conservation Project, including critical analysis, development of non-destructive testing methodologies and capturing history.

CHAPTER THREE

This chapter captures the work that has been continuing at the Opera House since the conclusion of the Concrete Conservation Project in mid-2016. It includes work to date on implementing the Concrete Conservation Framework.

The Sydney Opera House proposed Concrete Conservation Framework is included as **Appendix A**.

Chapter 1

ABOUT THE OPERA HOUSE

"The people of Sydney have made the Opera House a signature for Sydney, which you see everywhere in the world... but nobody is ever in doubt that this means Sydney and this means Australia."

- Jørn Utzon, Design Principles, 2002

Tubowgule and the Gadigal

The setting of the Opera House comes with its own rich and ancient heritage. Known to the local Gadigal people as Tubowgule, Bennelong Point was for thousands of years a special meeting place for sharing stories, songs, music, dance and food. With the Opera House standing on the site, it remains so today.

Imagining an Opera House

The Opera House was conceived with sky-high ambitions – nothing less than to 'help mould a better and more enlightened community', to use then-NSW Premier Joseph Cahill's words. "Surely it is proper in establishing an opera house that it should (be) an edifice that will be a credit to the State not only today but also for hundreds of years," Cahill went on to say in 1954.

By the time the Opera House opened in 1973, its significance was already becoming apparent. In a short space in time it was embraced as an emblem of Australia, and talk of heritage listing began. State Heritage listing came just 30 years later, and by its 34th year the site was World Heritage listed.

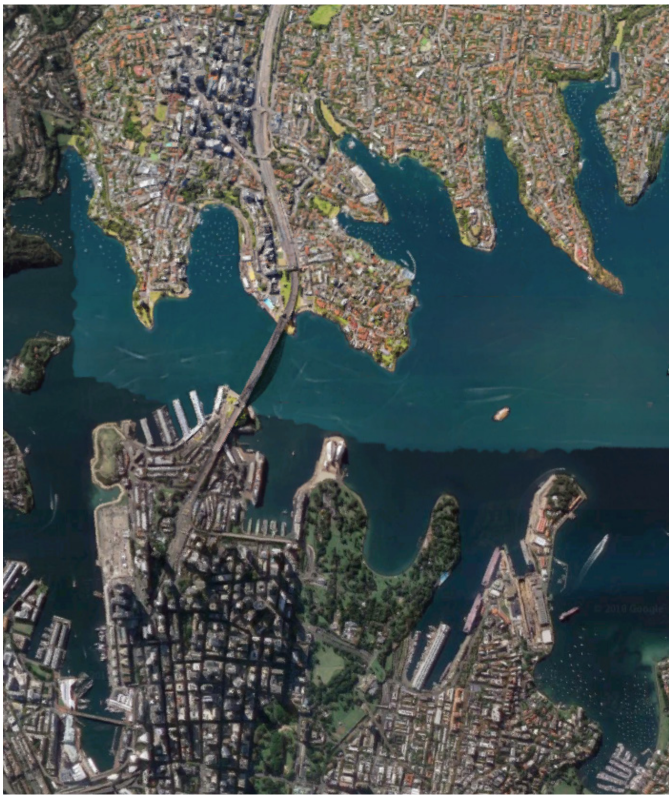
The Sydney Opera House is a building inspired by nature, and yet it is constructed primarily of modern man-made materials. The **Utzon Design Principles** (2002) underline in Utzon's own words the inspiration he drew from the building's harbour setting and nature's organic forms, colours and light.

UNESCO's 2007 World Heritage listing recognises Jørn Utzon's 'masterpiece of human creative genius' as 'a great urban sculpture set in a remarkable waterscape, at the tip of a peninsula', hailing its design as 'an extraordinary interpretation and response to the setting in Sydney Harbour'.

Timeline

1956	Design competition announced
1958	Danish Architect Jørn Utzon announced as competition winner
1959	Stage 1 Construction commenced
1962	Stage 2 Construction commenced
1967	Stage 3 Construction commenced
1973	Opening
2003	State Heritage listing
2005	National Heritage listing
2007	World Heritage listing
2018	Present day

250-300 years life expectancy



438.1 hectares

World Heritage Buffer Zone - 438.1 hectares of land and water lining Sydney Harbour with the line-of-sight to the Sydney Opera House.

5.8 hectares

Bennelong Point peninsula on the southern shore of Sydney Harbour, upon which the Opera House stands.

183 metres

Length of building footprint.

120 metres

Width of building footprint.

67 metres

Height of the Opera House's tallest sail above sea level (about 20 storeys).

102

Different sizes of tile lids used to line the concrete ribs and secure the roof tiles.

3,382

Number of tile lids used to line the concrete ribs and secure the roof tiles.

2,200

Number of pre-cast concrete ribs, post-tensioned with vertical and lateral steel reinforcement, used as an exposed architectural finish and to support the Opera House roof structure.

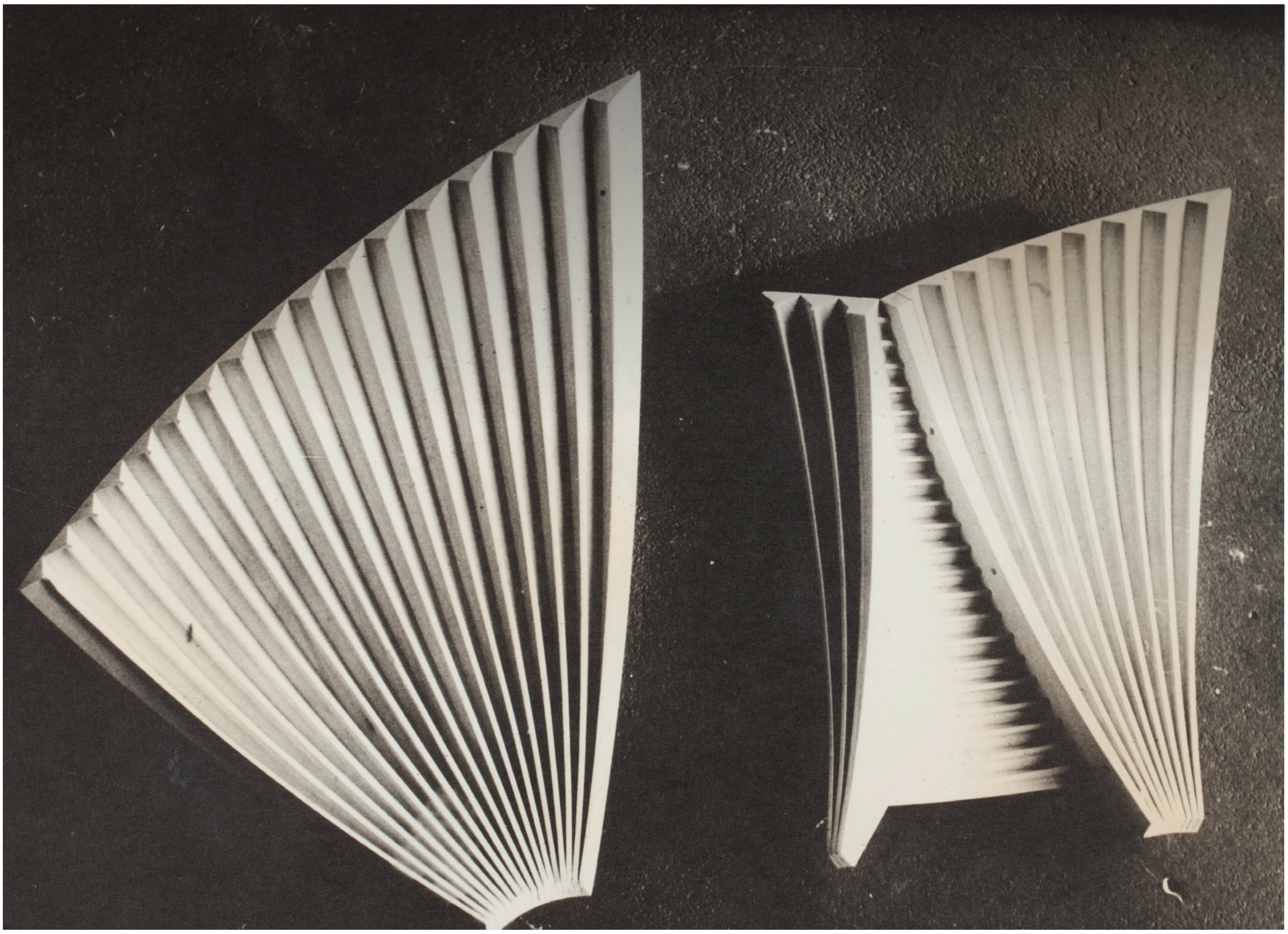
940,840

Number of ceramic tiles covering the entire Opera House roof.

A MASTERPIECE OF HUMAN CREATIVE GENIUS

"Sydney Opera House is not the kind of building which often comes within the orbit of the structural engineer. It is an adventure in building ... Because the circumstances under which it is being built are so unusual, and because its problems are so difficult, it has created unique opportunities, both in the design office and on the site ... The structure now standing in Sydney Harbour is the result not only of much toil and sweat but also of an unprecedented collaboration between architect, engineer and contractor ... we stretched ourselves to the limits of our skills."

- Arup & Zunz 1988: pp3–5



[1] Arup, O and Zunz, J 1969, 'Sydney Opera House', Structural Engineer, March 1969. Reprinted in The Arup Journal, October 1973 and in Sydney Opera House Reprint Series No. 1, 1988.

Sydney Opera House epitomises the late 20th century's daring use of modern concrete design and construction techniques. The building is famous for its innovative use of exposed structural concrete as a key architectural feature.

The Opera House is a building ahead of its time. The inspired concept required the consolidated genius of Architect Jørn Utzon and Structural Engineer Ove Arup, working in collaboration with the building contractors Civil & Civic (Stage 1) and M.R. Hornibrook (Stage 2), to invent new technologies and materials and create the means to build it.

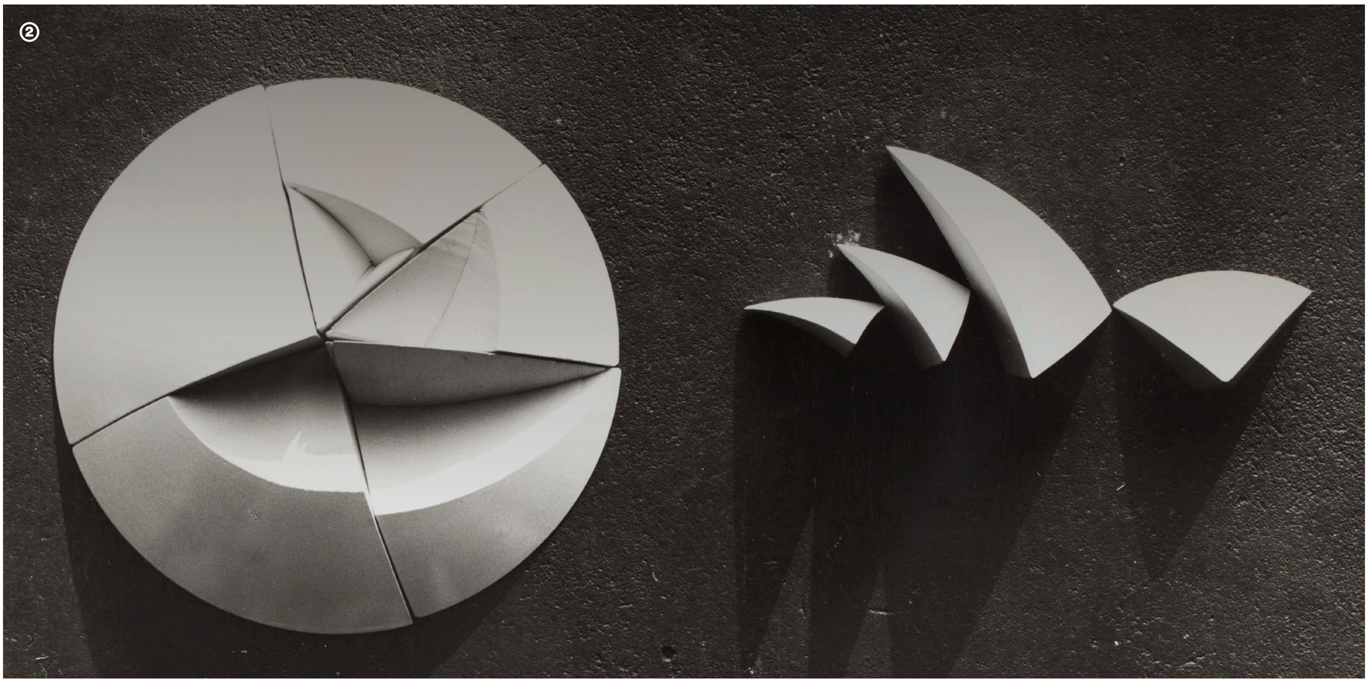
"The Sydney Opera House is often thought of as being constructed in three stages and this is useful in understanding the history of the three key elements of its architectural composition: the podium (stage 1: 1958–1961), the vaulted shells (stage 2: 1962–1967) and the glass walls and interiors (stage 3: 1967–1973)."[2]

"Design and construction were closely intertwined and this was a distinctive feature of the Sydney Opera House. Utzon's unique design together with his radical approach to the construction of the building fostered an exceptional collaborative and innovative environment. His collaborative model marked a break from conventional architectural practice at the time."[3]
The crowning achievement of the collaboration between architect, engineer and contractor is the soaring roof sails. There was no precedent anywhere in the world for building the sails, which needed to be self-supporting.

After twelve trial schemes, Utzon delivered the 'Spherical Solution' to the Sydney Opera House Trust in the Yellow Book (1962). The ten roof sails are built from segments of the same sphere, 75 metres in diameter. The simplicity of the 'Spherical Solution' enabled the post-tensioned system of pre-cast concrete ribs to be mass produced on site, offering both design coherence and economies of scale.

In 2003, Jørn Utzon received the Pritzker Prize, which formally recognised that the Sydney Opera House was 'one of the greatest buildings of the twentieth century' and 'an image of great beauty known throughout the world'.

②



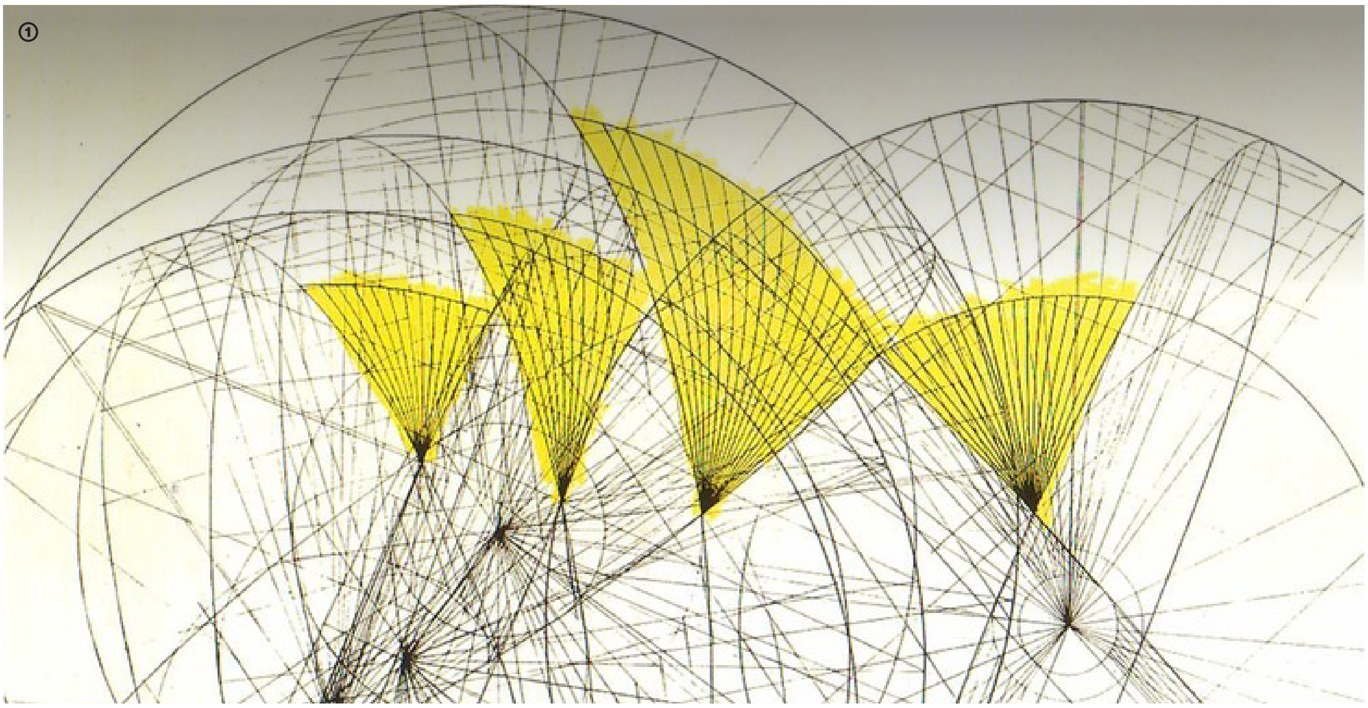
[2] Commonwealth of Australia, Sydney Opera House: Nomination by the Government of Australia for Inscription on the World Heritage List, 2006 p.23 [3] ibid

OUTSTANDING ACHIEVEMENTS IN STRUCTURAL ENGINEERING & TECHNICAL INNOVATION

The realisation of Utzon's design required ground-breaking research and development in several engineering fields involving close collaboration between the engineering design team and university teams in Britain and Australia.

Engineering and technological feats developed during the design and construction of the Opera House include:

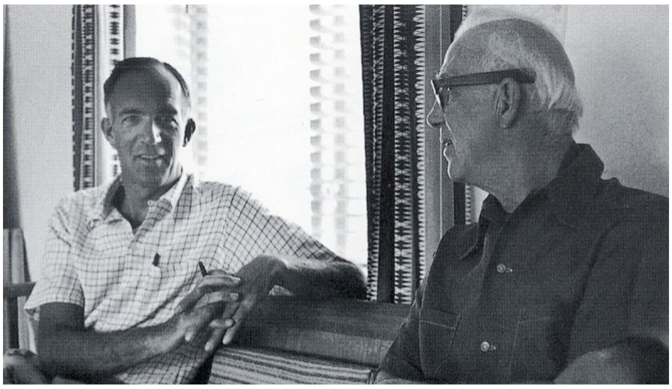
- Ove Arup designed folded concrete beams to support the podium structure. By integrating the techniques of folded plate structures and pre-stressing, Arup's innovations enabled the creation of expansive open spaces within the podium, such as the Box Office Foyer, without the need for structural columns.
- The Opera House is one of the first buildings in the world to make use of computers in design. The exacting geometric calculations necessary to build the sails could only be achieved using this new technology.
- Ove Arup & Partners were a pioneer of wind tunnel testing for buildings, during the design of the sails. This is now common practice in design for large buildings all over the world.
- An adjustable mounting and assembly arch was invented for the project by a French contractor to M.R. Hornibrook to support the massive pre-cast rib segments. This removed the need for mass scaffolding to support the structure during construction.
- An innovative epoxy resin process was developed through research by the Cement and Concrete Association (England) and the University of New South Wales (Australia) to bond the rib segments together. This achieved the smooth concrete effect that was vital to Utzon's design for exposed surfaces.
- The glass walls in the Opera House pushed the boundaries of technology. The Opera House is the first large-scale example of glass used as a structural load bearing material in a building. In 1972, Ove Arup & Partners received an award for engineering excellence from the Association of Consulting Engineers of Australia.[4]

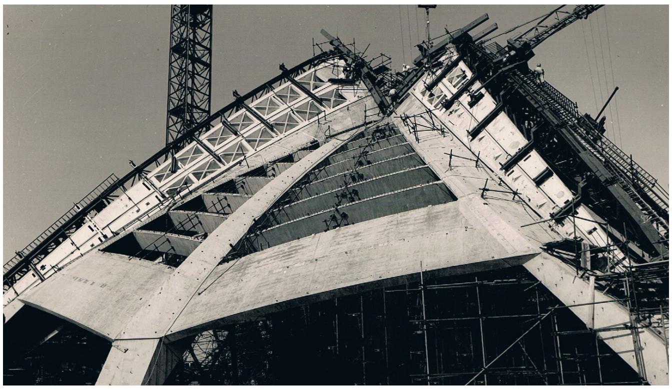


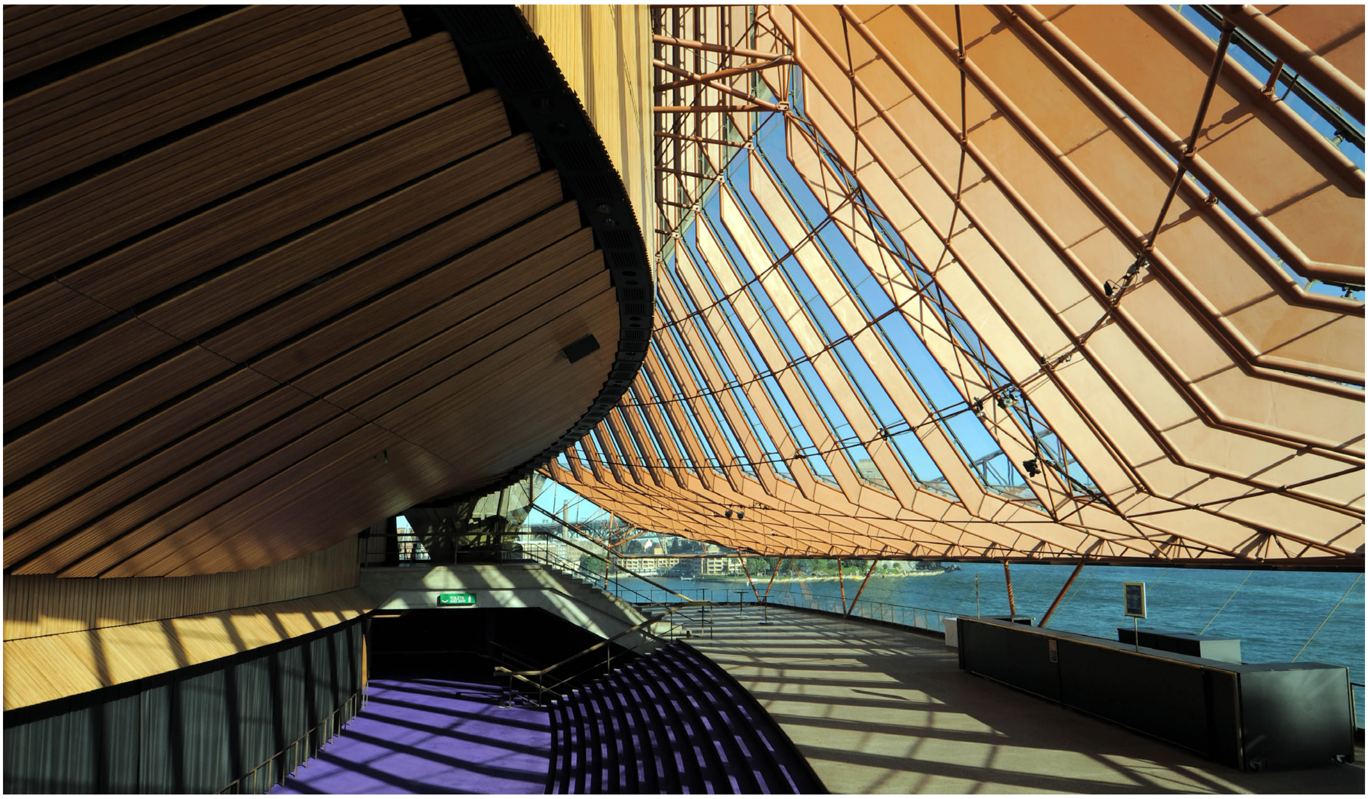
[4] Commonwealth of Australia, Sydney Opera House: Nomination by the Government of Australia for Inscription on the World Heritage List, 2006 p.36-42

“Engineering is not a science. Science studies particular events to find general laws. Engineering design makes use of the laws to solve a particular problem. In this it is more closely related to art or craft.”

- Ove Arup







THE DESIGN

In defining the scope of the Concrete Conservation Project, the project team decided to focus on three areas of research: the roof sails, the roof pedestals and the under-Broadwalk structures. There are certain aspects of the design of each of these structures that influence how concrete conservation may be approached.

This section describes how each building element was designed, which will aid understanding how the research inspections and testing were conceived for the Concrete Conservation Project.

“Usually things that are constructed have some sort of logical history and when this is known it is easier to take the right decisions at any one time.”

- Jørn Utzon, Design Principles 2002

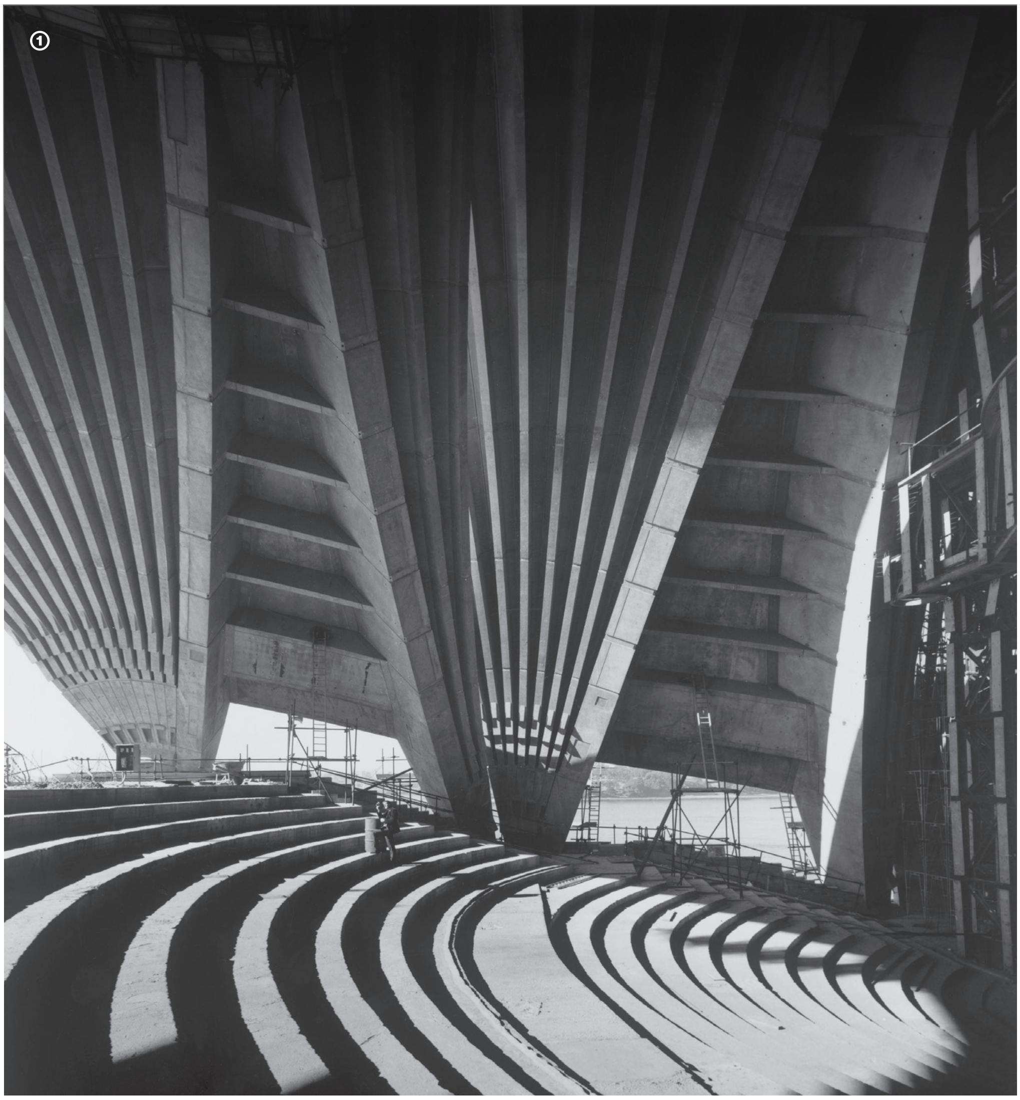
“I like to be at the edge of the possible.”

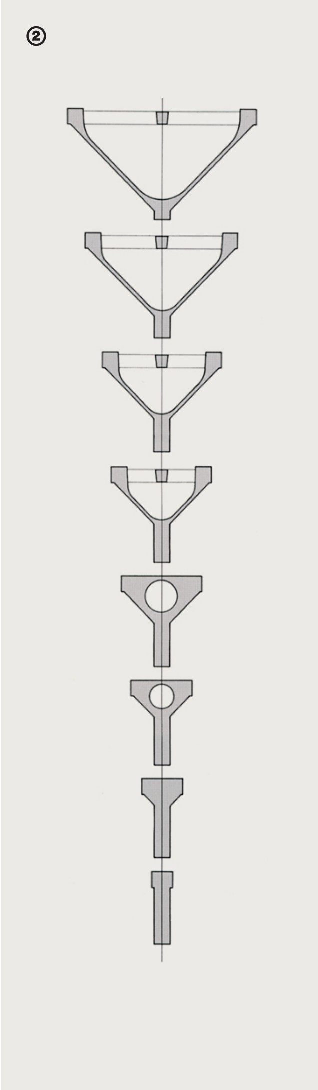
- Jørn Utzon

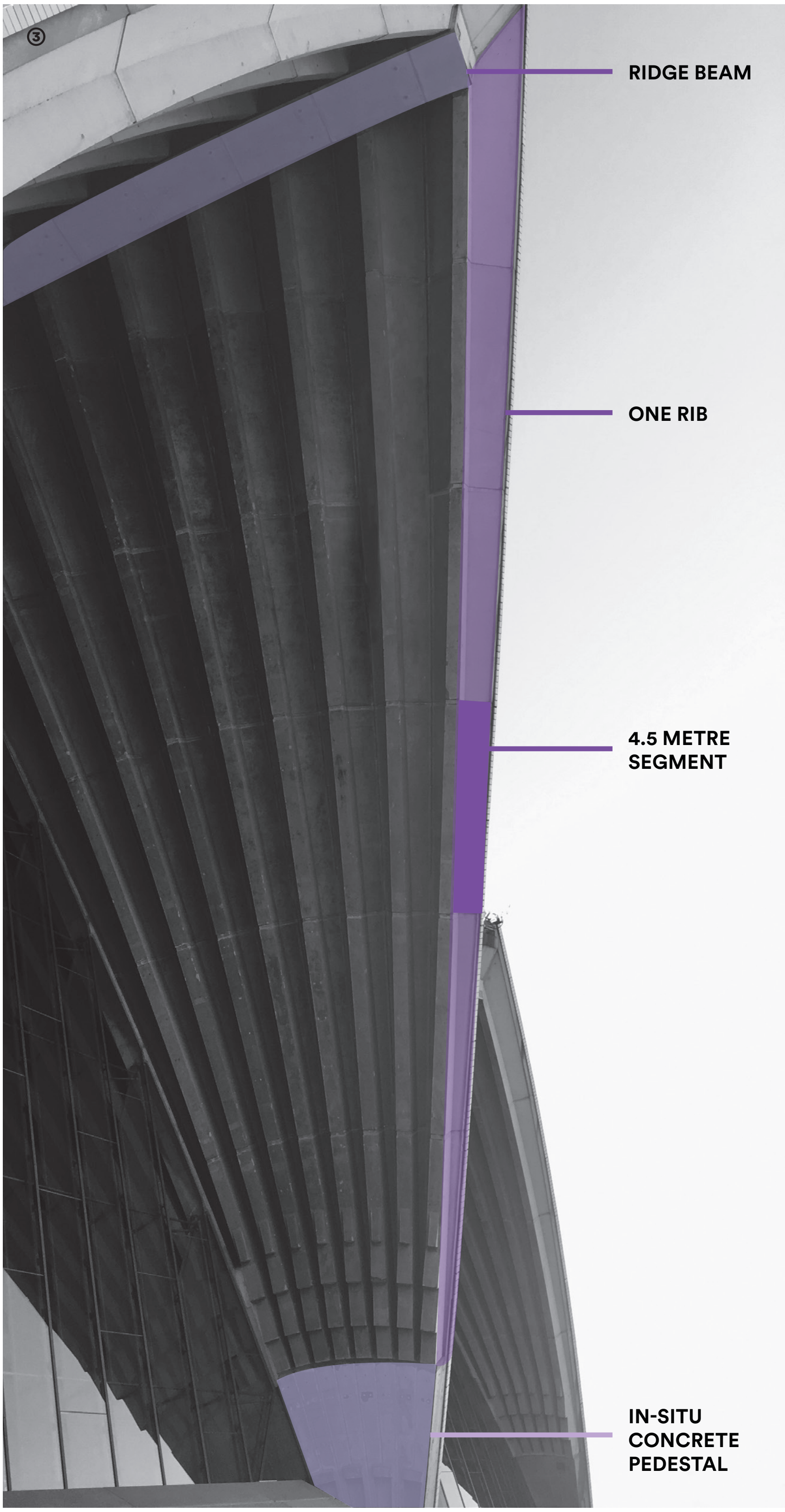
THE SAILS

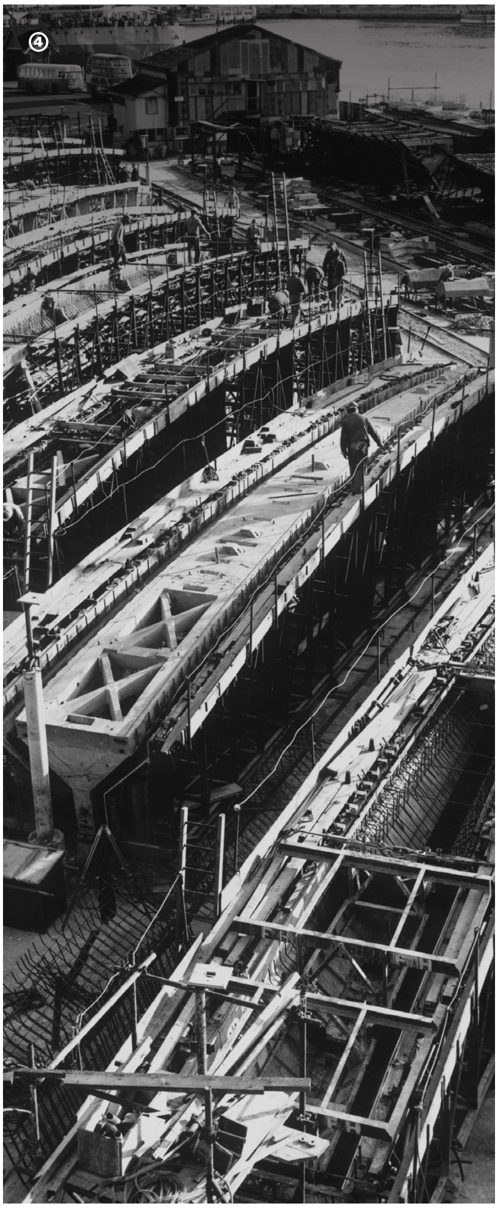
During construction of the Opera House, the pre-cast rib sections of the sails were cast with ducts to carry the steel stressing cables. In all, 4100 individual ducts with a total length of around 113 kilometres (70 miles) were created. The rib sections are bonded with an epoxy developed for the purpose during construction. After post-tensioning was completed, the ducts were pumped full of grout to seal the steel cables from the outside elements.

The rib structures were clad in 3,382 chevron-shaped prefabricated concrete tile lids, supporting around a million ceramic tiles. The tile lids have a slight spherical curve. The tile lids are bolted to the rib structure and sealed with epoxy polyurethane sealant. A protective epoxy grout is used between the individual tiles.









① Pre-cast rib element

② Pre-cast rib sections

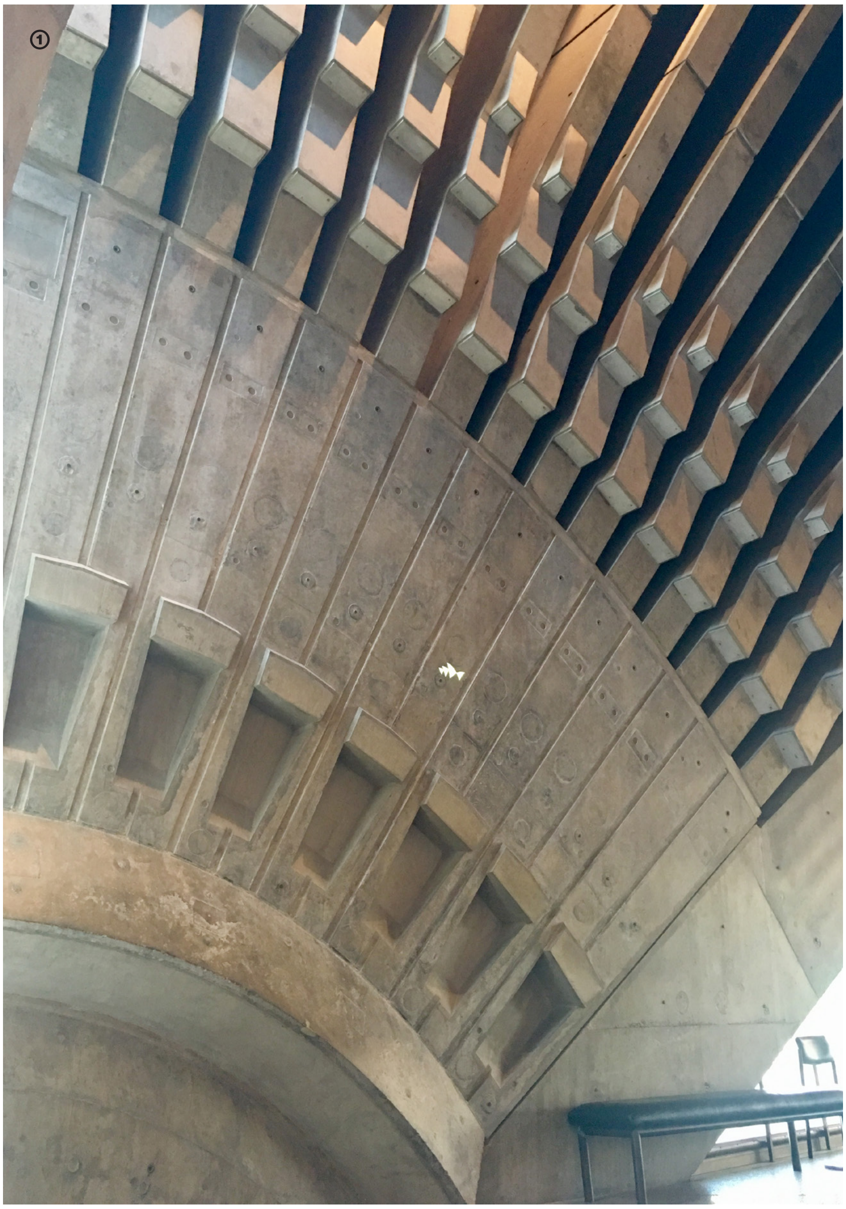
③ Rib elements tacked to make the sails

④ Ribs being cast on site

THE PEDESTALS

The points from which the sail ribs rise from the podium, and connect to the foundation columns, are known as the Pedestals. The Pedestals are made of reinforced concrete, cast in-situ, and can be seen on the building's exterior below the line of ceramic tiles, and in the interiors of the foyers to the Concert Hall and Joan Sutherland Theatre.

The concrete in the Pedestals is completely exposed to weather and the marine environment, and human contact.



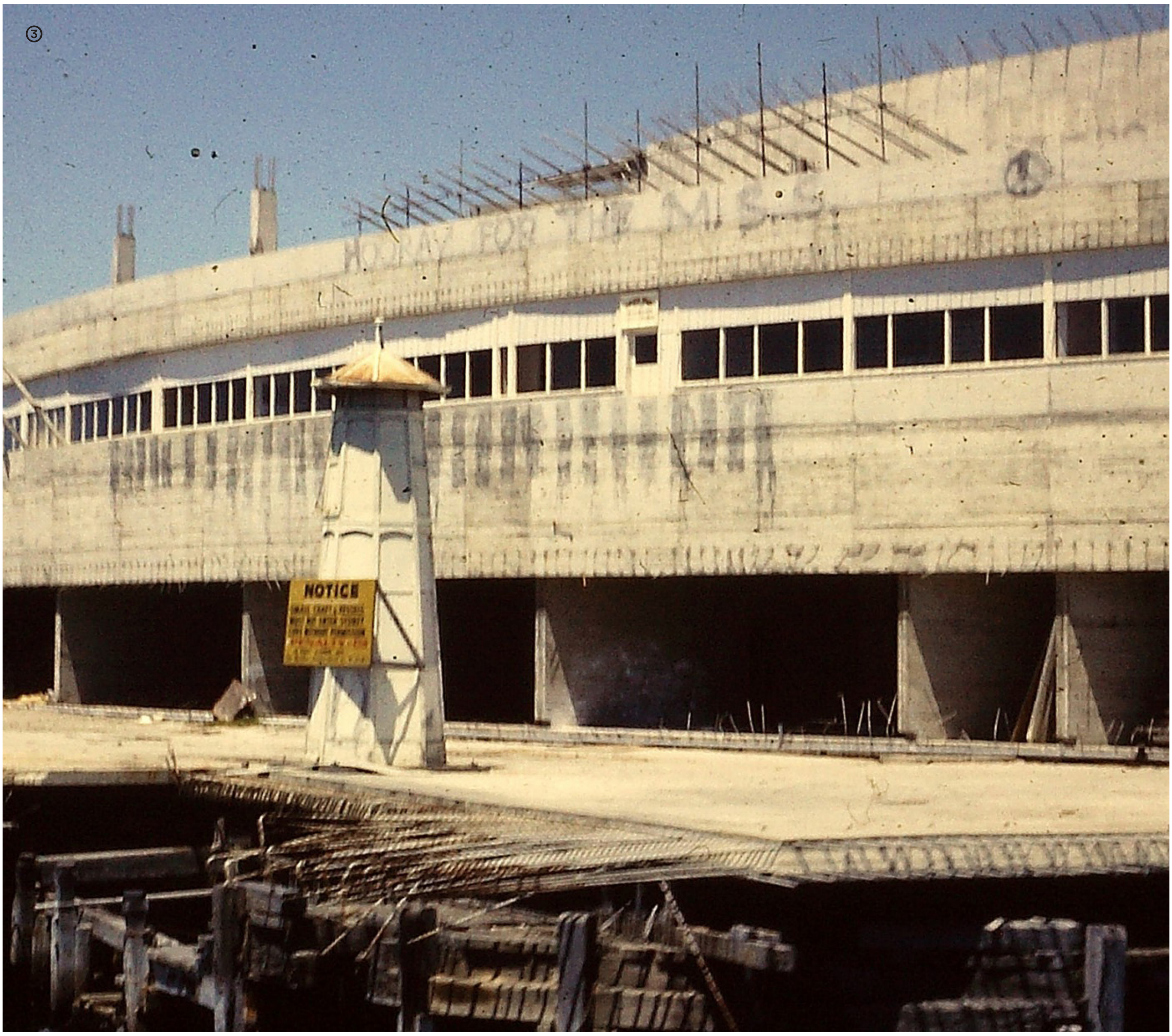
① In-situ concrete pedestal

BROADWALK STRUCTURES

The Opera House is built on a narrow peninsula of land on the south shore of Sydney Harbour. The Western Broadwalk and Northern Broadwalk rest on steel reinforced concrete piers, which are embedded into the harbour floor. Granite aggregate slabs are used to clad the Broadwalks.

③ Aerial view of Western and Northern Broadwalks

④ Northern Broadwalk under construction, 1962



CONSERVATION MANAGEMENT

“One of the indisputable masterpieces of human creativity, not only in the 20th century but in the history of humankind.”

- International Council Report on Monuments and Sites to the World Heritage Committee

As a heritage listed site, it is vital that the Opera House be conserved for future generations. The Sydney Opera House Trust has established a robust conservation management system that includes independent expert advice, policies and strategic documentation, and regular monitoring, preventative and corrective maintenance of the building structure.

GOVERNANCE STRUCTURE

Sydney Opera House Trust	Building and Heritage Committee	The Building and Heritage Committee is a sub-committee of the Sydney Opera House Trust, with a delegated authority to oversee and monitor building, conservation and heritage matters.
	Conservation Council	The Conservation Council is an advisory committee to the Sydney Opera House Trust and includes members from the Trust, management, and independent advisors from the NSW Heritage Office, NSW Department of Planning and Infrastructure, and industry representatives from the Indigenous, heritage and architectural communities.
	Eminent Architects Panel	The Eminent Architects Panel, chaired by the NSW Government Architect, advises the Trust on architectural design matters and includes five highly experienced and award-winning architects. Jan Utzon, son of Opera House architect Jørn Utzon, is a member.

POLICY & STRATEGIC DOCUMENTS

A hierarchy of documentation guides Opera House management towards meeting its heritage conservation obligations. There are legislative obligations that must be met, and this is achieved using various policy and strategic documents.

The visionary **Utzon Design Principles** (2002) and the policies of the **Conservation Management Plan 4th Edition** together provide the framework for considered decision making.

Utzon Design Principles

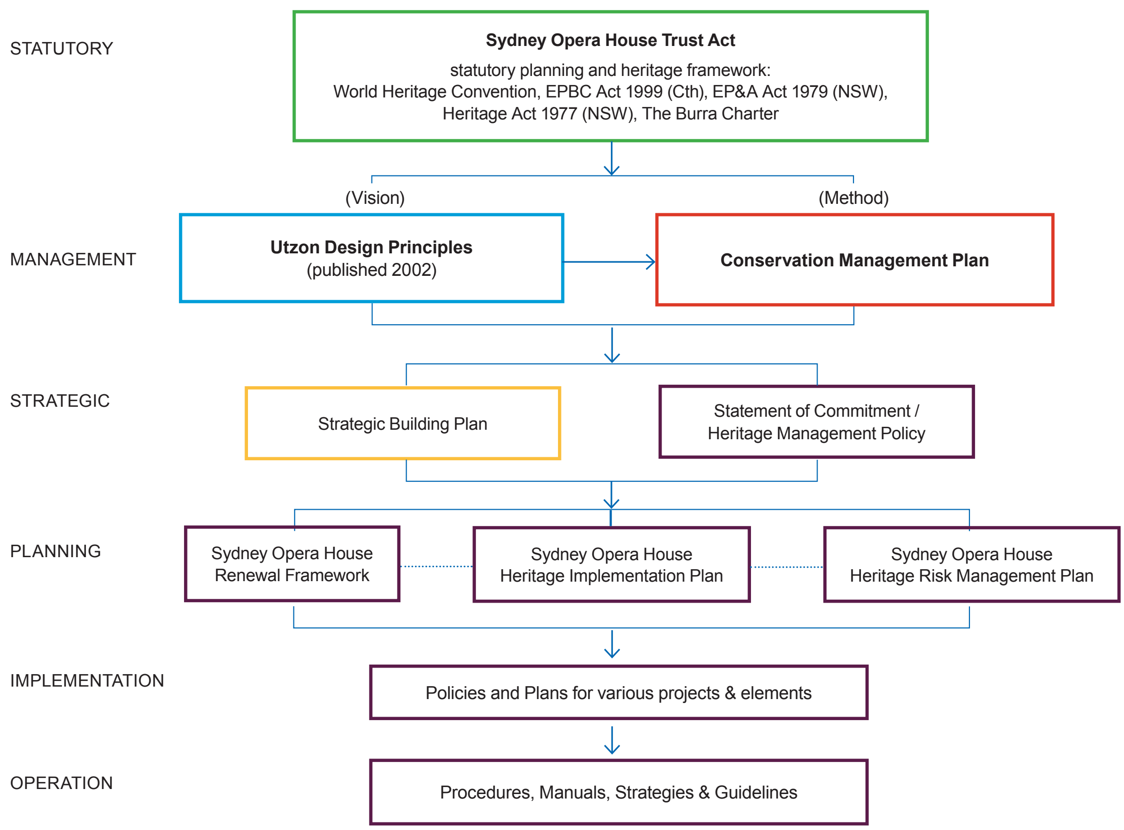
The Utzon Design Principles (2002) provide a permanent record of Utzon's original vision for the Opera House, as well as his views about its future, in his own words. This informs the parameters within which the building may evolve and develop to meet changing demands, while conserving the heritage values of the site and the intent of the original vision.

Conservation Management Plan

The Conservation Management Plan 4th Edition is one of the chief guiding documents on matters concerning the conservation of the Outstanding Universal Values of the Opera House. It sets out 'how to retain' significance in relation to Utzon's principles and how to implement and manage change.

The Sydney Opera House Conservation Management Plan is widely regarded as a benchmark in the field of conservation management. It defines the heritage significance of various elements of the site and the building's fabric. Concrete assets are assigned their level of significance based on this grading system.

The Conservation Management Plan contains detailed policies to conserve heritage values, guidance on maintenance, changes or upgrades, and procedures to manage the process of change.



Tolerance for Change

The concept of Tolerance for Change was first introduced in the Opera House Conservation Management Plan 4th Edition. Each element of the Opera House is assigned a Tolerance for Change score with respect to function, form, fabric and location. This aids the understanding of how much change a particular element can tolerate, and in what ways it may be changed.

In the Concrete Conservation Project, the Tolerance for Change of each concrete element was considered when determining appropriate testing and maintenance methodologies.

See example below:

Tolerance for Change

element:
Roof shells externally

significance ranking **A**

Three groupings of soaring, curved, concrete framed roof shells, clad with white ceramic tiled lid panels, surmounted by fine curved bronze lightning rails and infilled by glass walls

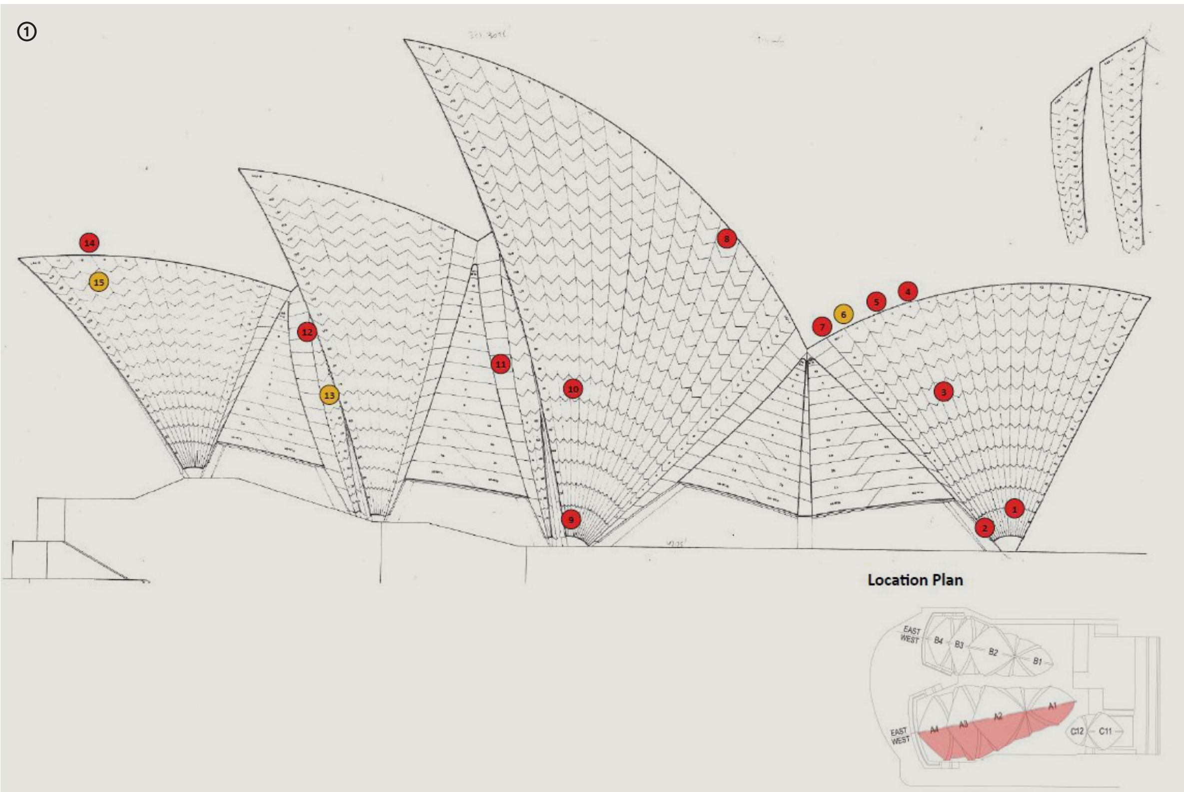
selected components:	**Tolerance for Change** 1 = Low tolerance 2 = Moderate tolerance 3 = High tolerance				**Further Considerations** (to be read in conjunction with the relevant policy section for each element)
	Form	Fabric	Function	Location	
Glazed tiles	1	1	1	1	Maintenance with replacement only where necessary. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.10.
Tile lids	1	1	1	1	Maintenance with replacement only where necessary. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.10.
Concrete ribs assembled from prefabricated elements supported on fan shaped pedestals	1	1	1	1	Maintenance only. Monitoring required to ensure structural integrity and finish are maintained. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.3. Preservation treatment may be required to protect pedestals in accordance with Policies 4.6, 7.2, 18.6, 18.7 and 18.8. Refer to intrusive items below.
Lightning rails – stainless steel	1	1	1	1	Materials and configuration are most important. Refer to discussion and policies in Section 4.7.2.
Deeply recessed bronze louvre walls infilling spaces between shell ends	2	1	2	1	Repeated and standardised bronze components geometrically arranged to complement the ribbed structure are most important factors. Refer to discussion and policies in Section 4.7.3.
Glass walls and supporting structures	2	2	1	1	Maintain as existing unless 'Major change' applies. Minor modifications permitted in accordance with Policy 4.4. Refer to discussion and policies in Section 4.7.3.
Shell uplighting at base of end pedestals (north and south)	3	3	2	1	Refer to discussion and policies in Section 4.14 *Lighting*.
Recent surface treatment of concrete pedestals externally	**Intrusive**				Explore less intrusive means of managing concrete deterioration, and protecting and exposing original surface – refer to Section 4.18.3 *Treatment of unpainted and precast off-form concrete*, and Policy 18.6.
Nose lights on shells	**Intrusive**				Both the fixtures and the glare are intrusive. Explore less intrusive means of lighting public space – refer to Section 4.14.2 *Lighting of Forecourt, Broadwalk and Podium (monumental) steps*.

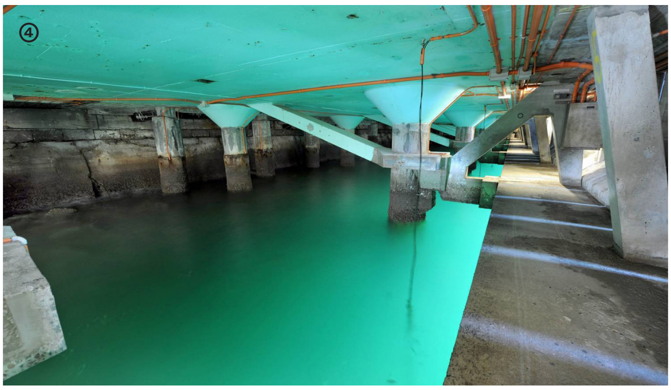
CONCRETE CONSERVATION

The Opera House has a regular program of condition monitoring, preventative and corrective maintenance for all areas of the building fabric. In the case of concrete conservation, Arup is engaged to provide inspections and interpretation of the data to make recommendations regarding the frequency and type of future inspections. A schedule of works is then developed and scoped accordingly.

The program includes:

- tap testing tiles
- roof sealant inspections
- concrete cover surveys in the pedestals
- removal of organic growth
- cathodic protection maintenance and monitoring
- monitoring seawall skirting panels and mounting systems
- monitoring of reinforced concrete condition beneath the Broadwalks





① Tile-tapping inspection on sails, Concert Hall west elevation

② Pedestal - before sacrificial coating

③ Pedestal - with sacrificial coating

④ Concrete sub-structure under the Western Broadwalk

⑤ Seawall skirting panels

⑥ Seawall skirting panel deterioration

Chapter 2

CONCRETE CONSERVATION PROJECT

"Methods to reinstate and maintain the alkalinity, integrity and condition of exposed concrete above the water should be explored and tested."

- Alan Croker, Conservation Management Plan 4th Edition (2017)

Project Overview

The concrete in the Opera House has been exposed to marine weathering and the effects of human interaction for more than 50 years. With few precedents, the custodians of the site are challenged with employing the most effective methods to monitor and conserve the condition of the concrete. The goal of this project was to develop best practice strategies for long term conservation. This would ensure the building achieves its design life of 250 years and beyond.

In 2014, the Getty Foundation invited the Opera House to submit a funding proposal for a concrete conservation study. The project aimed to develop an approach to concrete conservation that would bring together disparate data into an efficient and effective program to:

- facilitate understanding of concrete and dissemination of knowledge
- influence future research
- address knowledge gaps
- create a long term strategy for preventative and remedial maintenance for the Opera House
- build digital management tools to support concrete conservation

The Opera House convened a project steering committee, drawing on the expertise of Conservation Council members Sheridan Burke and Dr John Nutt (retired) to advise, respectively, on the heritage conservation and technical concrete aspects of the project.

Dr Nutt, who had worked for the structural engineering firm Arup during construction of the Opera House, helped focus the areas of study to the roof sails and pedestals. Greg McTaggart, Director Building also prioritised the structures under the Broadwalks, where concrete is directly exposed to seawater.

These areas were a high priority because:

- they play a critical part in the structure
- there are risks associated with exposure to the marine environment
- a project of this nature provides opportunities to answer critical pieces of missing information that could reduce risks to the structure and significantly enhance the capacity to protect and conserve the sail structures for future generations

The group understood that the issue of concrete conservation was multi-faceted, and determined that a multidisciplinary approach would be needed to achieve the desired results. The project required collaboration between the fields of architecture, engineering and heritage conservation. It also required a scientific approach and off-site testing facilities to enable methodologies to be developed and tested away from the Opera House building. A partnership with a university was sought.

After reviewing the range of disciplines of study available at several universities, the University of Sydney emerged as offering the best combination of faculties to suit the project. The choice had other advantages including proximity to the Opera House, an excellent academic reputation, and solid international connections with experts in the study of concrete.

Professor Kim Rasmussen and Professor Gianluca Ranzi joined the steering committee and a formal partnership was entered into with the University of Sydney. Professor Ranzi became responsible for driving the academic aspects of the project and leading the research.

Building on a partnership that has existed between the Opera House and Arup since the early stages of design in the late 1950s, Mike Cook, Arup Associate Principal, Transport & Resources, joined the project steering committee.

The project was structured in three parts, working concurrently:

PART ONE – CRITICAL ANALYSIS

University students in engineering, architecture, heritage conservation and related disciplines were engaged to complete research and critical analysis on the concrete studies and on-site trials that have been conducted during the Opera House's life, and International case studies of conservation strategies adopted for mid-century heritage concrete buildings. This information was collected into a consolidated knowledge bank.

PART TWO - INVESTIGATIONS & NON-DESTRUCTIVE TESTING

Practical investigations and non-destructive testing methodologies were developed based on the identified knowledge gaps and priorities. These included condition assessment of the concrete under the tile lids, studies on the environmental impacts on the roof pedestals, and inspection of the concrete in the Northern Broadwalk under-structure.

PART THREE – CONCRETE CONSERVATION FRAMEWORK

Development of a Concrete Conservation Framework - an interactive interface, integrated with the 3D Building Information Model - to ensure the concrete is conserved in the best condition possible, while also conserving its authenticity. The framework involved creating a concrete classification system that could be used in recording and interpreting condition monitoring results.

The project brought together engineers, students, academics, heritage specialists and concrete industry professionals. A group of exceptional people – some of whom worked on the original construction of the building – volunteered their time to share oral histories with the project team. These first-hand accounts of the construction of the Opera House have become an invaluable resource for the current and future custodians of the building.

Our Partners

UNIVERSITY OF SYDNEY

The University of Sydney is Australia's first university and is regarded as one of the most prestigious. It is ranked as one of the most reputable universities in the world. With Professor Gianluca Ranzi, who specialises in the fields of structural engineering, architectural science and heritage conservation, representing the broader university, this partnership was a good fit with the project objectives.

The partnership with the University of Sydney was mutually beneficial. The Opera House received the benefits of focussed scientific research, access to laboratory facilities and advancement of non-destructive testing methodologies that were not possible in-house. Students received unprecedented exposure to a real-life case study on a World Heritage listed site, along with the opportunity to work closely with industry professionals in a multidisciplinary team.

The students became familiar with non-destructive testing techniques for concrete condition assessments that are usually not covered in undergraduate or post-graduate courses in Australia. This represented a great opportunity for the students to gain insight into the types of non-destructive testing measurements available for the condition assessment of concrete components.

Due to the multidisciplinary approach taken in the project, heritage conservation students were exposed to engineering concepts related to concrete structures, and engineering students became familiar with conservation principles relevant to 20th century concrete structures. This provided a special experience for the students to gain an understanding on how their specific disciplines fit and contribute to address real world problems.

ARUP

Arup has been providing consulting engineering services to the Opera House for nearly 60 years. The period between the initial appointment as Principal Engineers in 1957 and the official opening in 1973 is well recorded. By comparison, considerably less has been recorded about the investigations, studies, maintenance, repairs, modifications and major refurbishments that have been carried out in the 45 years since its opening.

Arup has contributed over 300 individual projects, on subjects as diverse as security, building diagnostics and façade engineering, theatre planning, and civil engineering and tunnelling. This wide-ranging and consistent set of commissions have involved a huge number of Arup individuals and specialisations from around the world – forming an unparalleled organisational repository of knowledge in the form of project records, archival materials and individual experiences.

As result of the Concrete Conservation Project, the considerable value of the knowledge of past projects held in Arup archives and retained in the memories of current and retired Arup staff has been realised, along with the importance of passing on this knowledge to future generations.

CRITICAL ANALYSIS: PART 1

Critical Analysis

Numerous studies have been completed on the Opera House concrete throughout its life, as part of routine maintenance and through capital projects. However, there was a need to locate, integrate and activate these reports, close knowledge gaps, and develop an interactive management framework for concrete conservation.

Professor Gianluca Ranzi from the University of Sydney Centre for Advanced Structural Engineering was involved in the different stages of the project, and coordinated connections with other faculties as required.

Dr Cameron Logan from the University of Sydney School of Architecture, Design and Planning was involved in the heritage conservation case studies performed on 20th century concrete structures.

Associate Professor Francesco Fiorito from the School of Architecture, Design and Planning was involved with the initial work of the conservation framework.

Osvaldo Vallati from the Centre for Advanced Structural Engineering was involved in the tile lid prototyping and the development of the non-destructive methodology for the tile tap testing.

Riccardo Luzzi from the Centre for Advanced Structural Engineering contributed to the construction of the tile lid prototype.

Twelve students of engineering, architecture and conservation from the University of Sydney were involved in the Critical Analysis stage. The students were assigned projects across six study areas.

Student study areas

PROJECT	OUTCOMES
Investigation of the condition assessment of the Northern Broadwalk under-structure	Engineering students Gabriel Garayalde and Samuel Lane reviewed the Opera House investigations received on the Northern Broadwalk under-structure. They familiarised themselves with a number of non-destructive testing techniques capable of providing insight into the durability of existing concrete structures, including the Ultrasonic Pulse Velocity, resistivity meters and the Torrent Concrete Permeability tester. They prepared and carried out an experimental study to evaluate the air permeability of concrete samples prepared with different concrete strengths, with the aim of evaluating the quality of the concrete present in the cover (the concrete layer that protects the reinforcement from aggressive attacks).

PROJECT	OUTCOMES
Degradation of the concrete surface of the roof pedestal	Masters student Anna McLaurin from the Faculty of Architecture, Design and Planning provided a careful account of the decision-making process involved in diagnosing and treating concrete deterioration on the roof pedestals. Her work analysed consultants' investigations and recommendations across several decades against the background of an evolving conservation framework for the Opera House. Engineering students Yunhe Ying and Hok Hin Lei reviewed the investigation reports related to the pedestals made available by the Opera House. Their work dealt with the degradation of concrete components and, after considering different sources of damage, focussed on the effects of chloride ingress. They developed an experimental setup to degrade concrete specimens and performed non-destructive testing using a resistivity meter to monitor their ability to characterise the known levels of damage induced in the concrete samples.
Review status of roof tile delamination	Lara Goldstein from the Faculty of Architecture, Design and Planning conducted research into the history of the tiles and tile lids, from design and testing in the 1960s to the condition assessments completed in the 1980s, 1990s and beyond. Scott Grant and Mitchell James Grech from the School of Civil Engineering reviewed existing Opera House investigation reports to gain insight into the types of damage commonly found during past inspections of the tiles. Following this research, an experimental program was defined focusing on detection of the bond conditions in ceramic tile lids using Infrared Thermography.
Non-destructive testing techniques for the evaluation of the tile lid conditions	Lara Goldstein from the Faculty of Architecture, Design and Planning focussed on non-destructive testing techniques suitable for the condition assessment of the tile lids.
Non-destructive testing techniques for the evaluation of the pre-stressed concrete members	Gordon Yao Heng Liang and Amara Kruaval from the School of Civil Engineering reviewed investigation reports provided by the Opera House related to the condition assessment of the roof sails. They prepared concrete specimens with known voids and pre-stressing duct installations to reflect possible scenarios encountered in the non-destructive testing of the pre-stressed concrete ribs. They used ultrasonic testing to identify the voids and ducts to be built in the laboratory specimens, and developed a useful testing arrangement to enable ultrasonic measurements to be taken at well-defined locations.
International case studies of conservation strategies adopted for mid-century heritage concrete buildings	Steven Barry and Recarda Barker from the Faculty of Architecture, Design and Planning focused on case studies of conservation strategies applied to modern heritage concrete buildings. Noting the comparisons that have sometimes been drawn between Sydney Opera House and Eero Saarinen's Kresge Auditorium at MIT (USA), Steven Barry investigated the history of the design, construction and conservation of Kresge. With the permission of the Sydney Opera House, Steven Barry presented his findings to a well-attended seminar organised by the Australian Institute of Architects Heritage Committee in August 2015. Recarda Barker's case studies consisted of the Penguin Pool at the Zoological Society Gardens in Regents Park (UK), the Unity Temple in Oak Park (USA) and the Promontory Apartments of Ludwig Mies van der Rohe (USA).

NON-DESTRUCTIVE TESTING: PART 2

Part two of the project enabled new technologies and advances in scientific research to be applied to questions about the current condition of the concrete in the Opera House, and help develop conservation strategies for the future.

Investigations assisted in understanding the:

- complexity of the structural elements
- original construction techniques
- application of internationally recognised repair methods
- requirements for suitable advanced non-destructive testing protocols for use at the Opera House
- available options for the conservation of the exposed concrete in the Opera House

Some of this work was completed in consultation with academics and technical staff from Europe. In 2015 and 2016, Associate Professor Massimiliano Bocciarelli, Associate Professor Cristina Tedeschi and Marco Cucchi (Politecnico di Milano), who have significant experience with conservation of heritage structures, spent time in Sydney during the project duration.

Intimate knowledge of the original construction techniques and the reasons behind certain decisions having been made at the time of construction was collected from experts who had worked on the Opera House site during construction in the 1960s. This work is further discussed in the Capturing History chapter of this report.

Practical experiments

Practical experiments were carried out in the laboratory environment. The undergraduate students involved in the project were able to gain insight into the setting up and preparation of concrete samples. The specimens were based on typical reinforced and pre-stressed concrete detailing and considered information of typical structural components of the Opera House available at the beginning of the project.

After the samples were completed, the students were able to gain insight into the use of non-destructive testing techniques for the condition assessment of concrete components and included the application of an ultrasonic pulse velocity tester, resistivity meters, infrared thermography and the Torrent concrete permeability tester.

Non-Destructive Testing Methodologies

GROUND PENETRATING RADAR

This was considered for evaluating the position of the steel reinforcement in the back side of the ribs. It was concluded that mesh present behind the tiles acted as a shield that inhibited accurate measurement from the external surface of the tile lid.

ULTRASONIC PULSE ECHO IMAGING

This technique was explored to evaluate possible air gaps present in the grouting around the pre-stressing strands in the concrete ribs.

ROBOT FOR INSPECTING THE SAILS

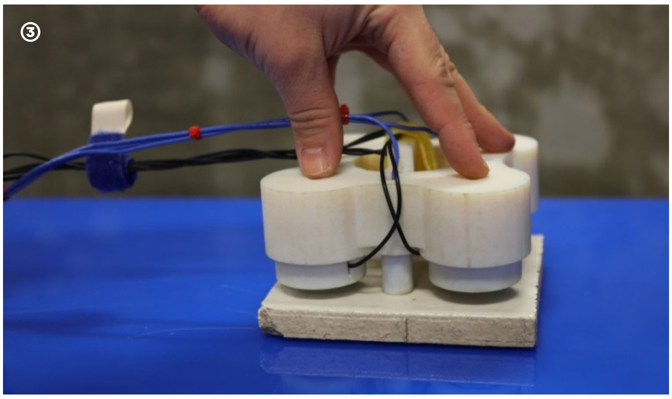
The University of Sydney team proposed the idea of developing a robot capable of climbing over the Opera House sails. A site visit took place to understand the site conditions and constraints for the support and movements of the robot on the sails. This idea has not progressed further due to the prohibitive cost, and the possibilities of emerging technology that shows promise in producing similar data more affordably.

REMOTE-SENSING VIBROMETER

The use of this technology was considered to monitor the relative movement between the roof sails and record vibrations in the sails.

VIBRATION SPEAKERS

To aid with condition assessment of the tiles, excitation by predefined sound frequencies induced to the tiles was applied using vibration speakers. This technique aimed at reproducing a condition assessment procedure similar to tile tapping, without the need for the hammer. The identification and monitoring of different sources of environmental noise, such as passing harbour vessels, that can produce vibration in the structure is being considered for possible future study.



① Students involved in concrete cover readings

② Hammer used by Arup for tapping testing of tiles

③ Application of vibration speakers to aid condition assessment of the tiles

④ Benchmarking samples in the lab

⑤ Students involved in on-site NDT ultrasonic testing

Sail Investigations

As the most recognisable aspect of the Opera House, and one of the areas most exposed to the elements, significant focus was given to investigations of the tiles and tile lids.

PORTABLE MOBILE TAPPING DEVICE:

The Opera House is clad with approximately one million ceramic tiles. The majority of these are original with the only significant change being the replacement of approximately 11,000 edge tiles in the early 1990s. In the last 10 years, less than 40 roof tiles have been replaced.

As part of the regular maintenance plan, a five yearly tap testing project is conducted by Arup, using skilled inspectors who abseil the structure to tap each tile and check for altered sound and changes in visual appearance.

The University of Sydney team suggested that this testing could be updated to include a microphone to capture the sound generated during the tap test, a force sensor to measure the force applied at the tip of the hammer and an infrared thermometer to evaluate the surface temperature of the tile.

This approach was pursued to embrace current testing protocols with the vision of establishing a database of measurements that could be used for the real-time condition assessment of the tiles and to create, over time, historical assessment profiles that could be available to future generations of building managers and inspectors.

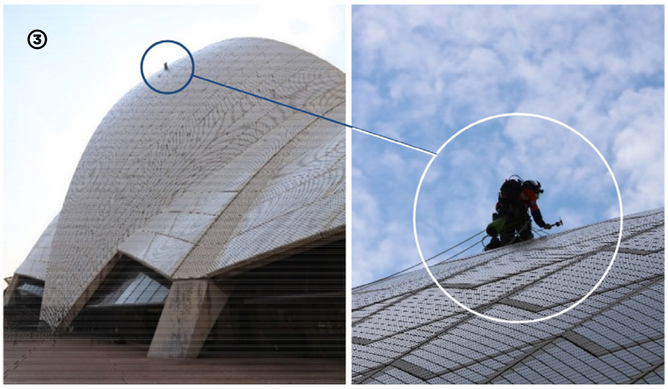
Some of the key challenges associated with the tile tap testing process consisted in correctly relating each site measurement to the location where it is taken within the structure and to effectively post-process measurements for the condition assessment and for the identification of possible situations requiring further attention.

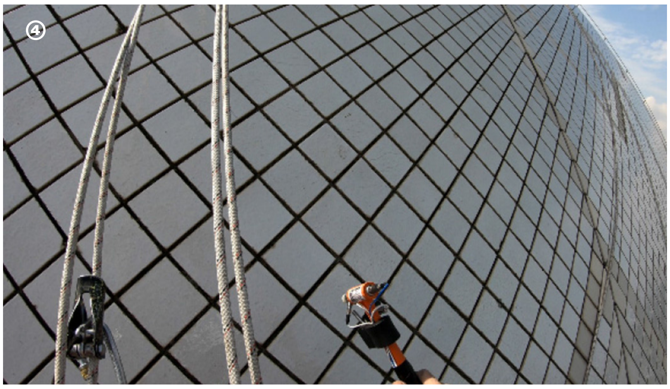
In the case of the Sydney Opera House, its complex geometry and large number of roof tiles (i.e. 940, 840 tiles) required a bespoke approach for the identification of the location of each tile tap test, for associating it to the recorded measurements and for its condition assessment.

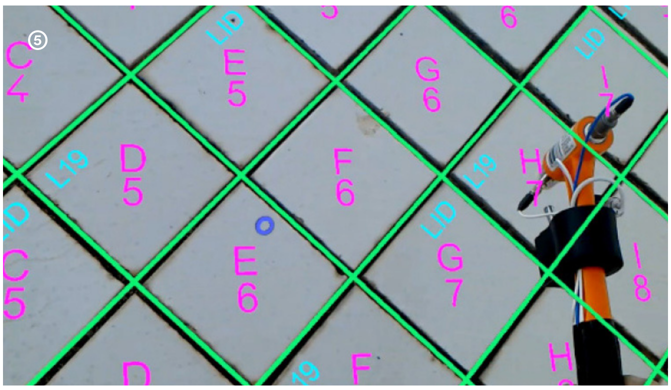
After considering a number of technologies, it was decided to develop and trial a methodology that relied on the use of the Microsoft HoloLens and of portable digital cameras. With this approach, an intelligent framework identifies the location of the tile tap test from the hologram overlapped on the structure and performs the condition assessment.

The outcome of the inspection process is presented visually by classifying the conditions of the tiles with a colour ranking scheme that varied between green to depict a tile in good conditions, orange to denote a tile in acceptable conditions and red to distinguish a tile in poor condition.

Different moments during the tile tap testing taken place in selected areas of the sails to trial the methodology are shown below.







① Initial prototype of the portable device developed as part of the project

② Operator performing tap testing of the tiles

③ Operator during tile tap testing using the proposed approach

④ View of operator during tap testing of the tiles

⑤ View of operator through the HoloLens during tap testing of the tiles

Tile Lids

The concrete ribs in the sails are clad in 3,382 chevron-shaped tile lids, which hold the ceramic tiles in place. Considering the complexity of the spherical geometry and the difficulty in accessing the tile lids on the structure, there was a need to create physical models of these components.

Information on the tile lid construction was gathered from Opera House reports, publications, Arup reports and drawings, and oral histories.

A tile lid model was built in the University of Sydney laboratory, based on the geometry of one third of tile lid R6. The geometry of the tile lid was established from the original Arup drawing No. 1112/3004.

A new construction methodology was developed for tile lid to achieve the 3D spherical geometry of the formwork due to the lack of information available on the original tile lid construction.

3D printing was considered for the formwork, but the team soon abandoned this idea due to the costs involved in achieving high precision 3D printed models. Other options considered, but not pursued beyond preliminary experiments included waffle arrangements of plywood formwork, and deforming a sheet of any material (such as metal and timber) to produce the required 3D shape.

The solution adopted in this project was achieved by recognising that the points of contact between the exterior spherical shape of the lid and the single tiles occurred only at the tiles' corners, because of the concave up shape of the formwork (as the tiles were placed face-down at the bottom of the formwork). To embrace the spherical shape a sloping surface was applied on top of the corner supports to ensure that the tile orientation could follow the exterior shape.

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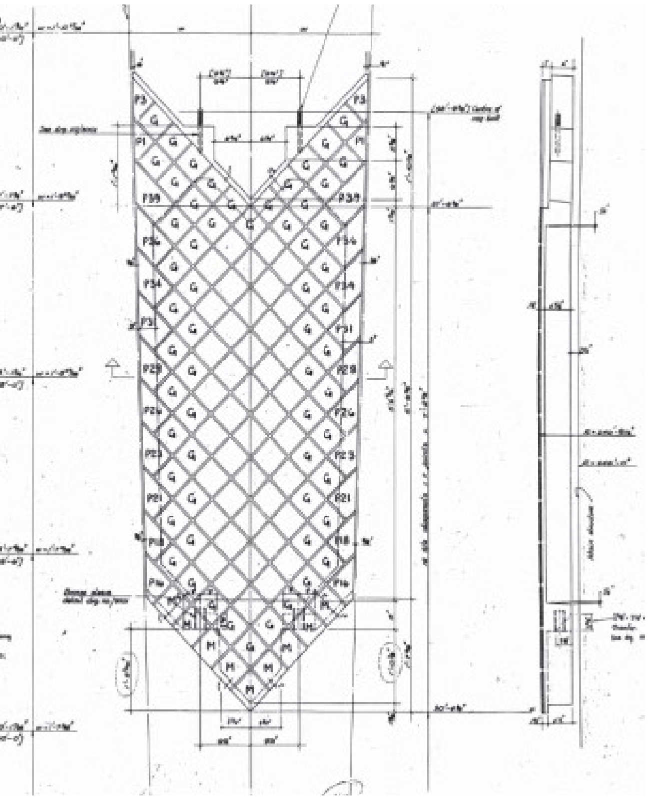

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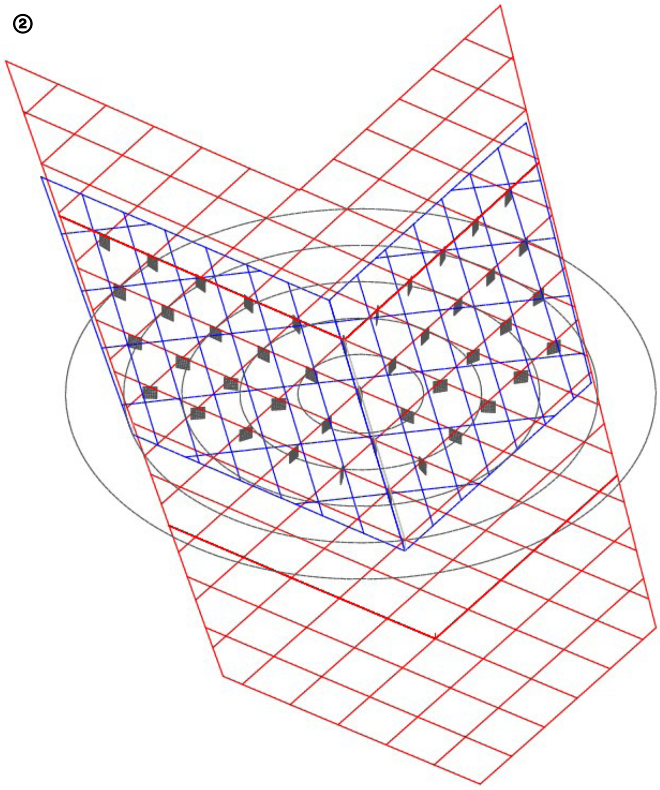
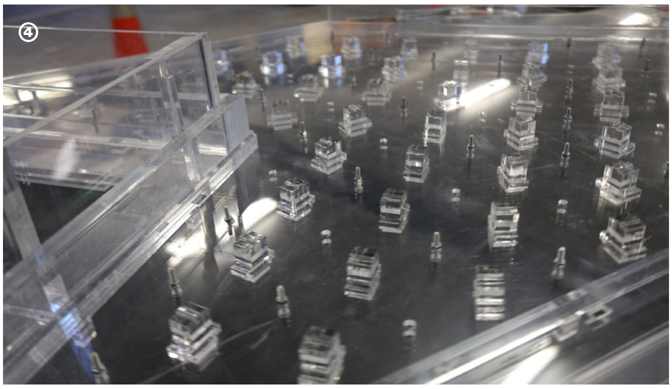
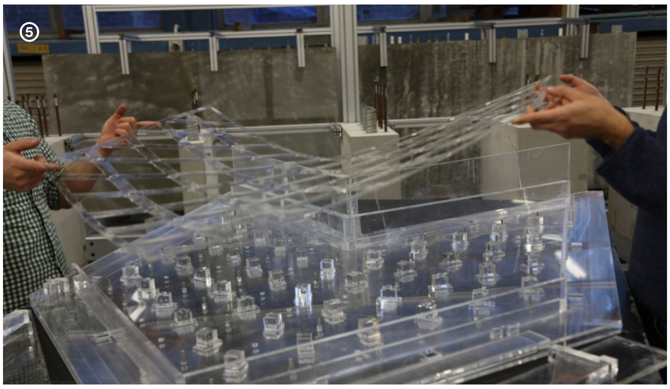
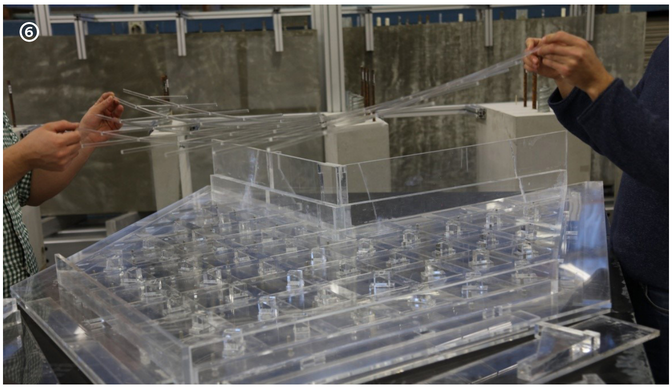
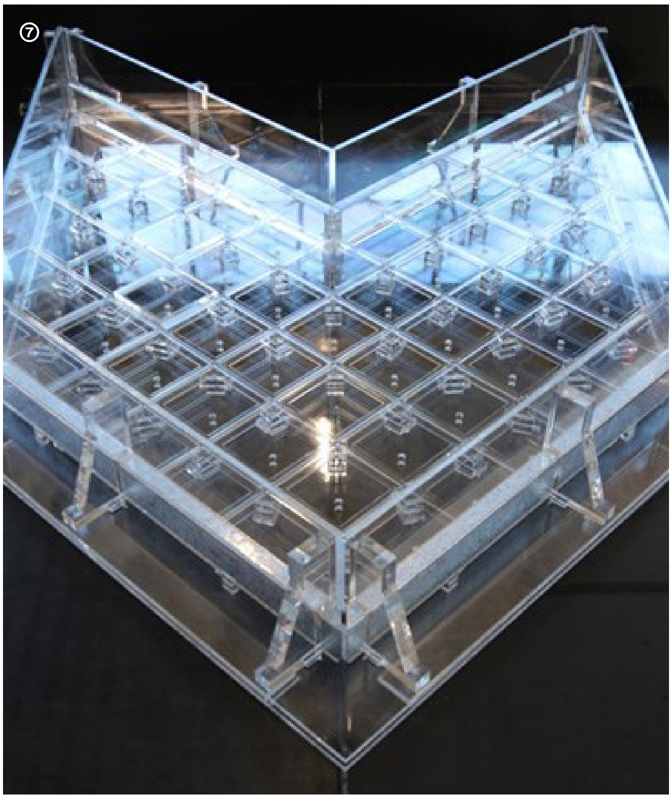
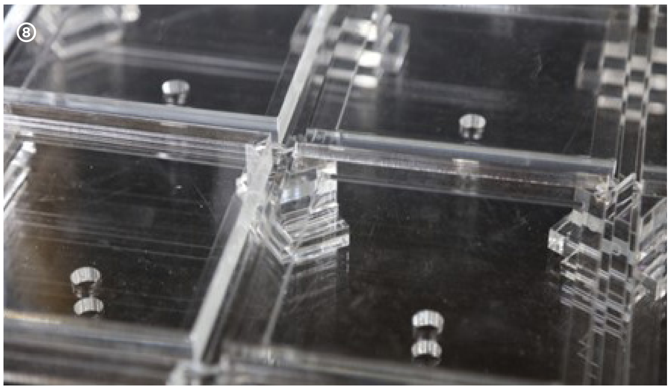


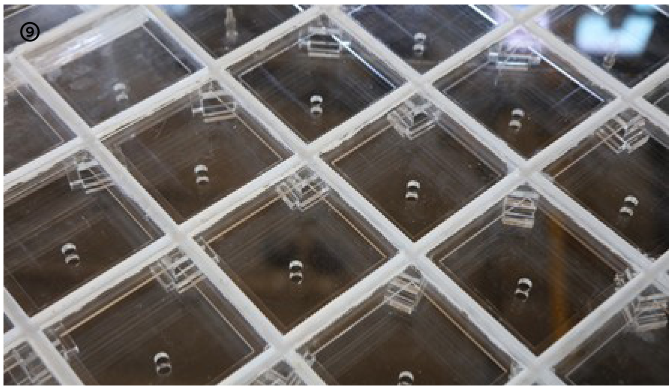












① Tile lid R6

② Selected portion of tile lid R6 reproduced in the laboratory prototype

③ Details of the column supports cut from 3D acrylic sheets

④ Layout of the support columns pointing towards the owest point in the formwork to create the 3D spherical shape

⑤ Installation of the acrylic mesh in the formwork to support the tile edges and corners, and to seal the gaps between adjacent tiles during casting

⑥ Acrylic mesh to be placed between tiles in place of the square aluminium strips used in the original tile lid construction

⑦ Overview of the acrylic formwork

⑧ Detail of the acrylic formwork showing the corner supports

⑨. Overview of the formwork after placement of the wax

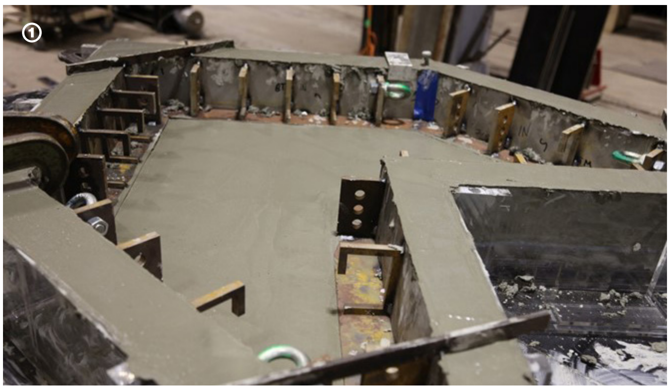
The spherical shape was achieved by pointing the individual supports, cut from 2D acrylic sheets, towards the lowest point in the formwork. The individual supports were numbered to avoid confusion during set up of the formwork, as each required slightly different dimensions.

For the purpose of the physical model, transparent acrylic tiles with same thickness and dimensions as the Opera House tiles were adopted. These proved to be useful in verifying the quality of the ferro-cement finish on the underside. Spare ceramic Opera House tiles were not used in the model to reserve the original tiles for future maintenance needs.

A flat mesh of thin acrylic material provided a supporting surface between adjacent supports. The acrylic tiles were then placed in position. The resulting acrylic finish was very good, and also enabled viewing into the internal structure in the model.

During the casting procedure, ferro-cement was first placed for the thin layer of the lid. Once this was levelled, the steel reinforcement of the ribs was placed in the formwork, followed by the internal metal formwork to provide the shape of the ribs.

As had been done during construction of the Opera House wax was placed between tiles in the model to prevent leakage of water or ferro-cement during the casting procedure.



Pedestal Investigations

The pedestals are a particularly prominent architectural feature, located in public areas crossed by more than 8 million visitors a year. They are of exceptional heritage significance and the impact of any decision to treat or not treat the concrete condition needs to be carefully evaluated with respect to potential impacts on the building's authenticity and integrity.

Heritage conservation expertise will always be employed to ensure any recommendations take into account the potential heritage impacts, as well as the results of scientific testing.

The scope of work carried out for the pedestals was defined after reviewing recent inspection reports, which determined that reductions in surface thickness and minor carbonation and chloride ingress since construction of the Opera House did not represent a threat to the structural condition of the pedestals. There are however, some areas of decreased coverage in specific localised areas, which may be treated on a case-by-case basis.

In the initial part of this work, the main aim was to reduce, if not completely eliminate, the rain runoff reaching the back faces of the pedestals.

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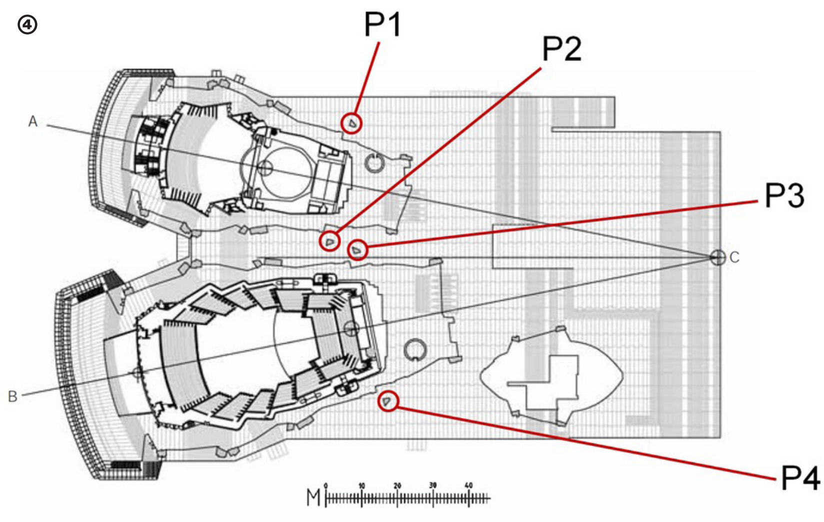

① Overview of the tile lid prototype after casting

② Tile lid prototype after removal of the side formwork

③ Tile lid prototype after completion

④ Plan showing pedestals of interest in first part of pedestal investigation


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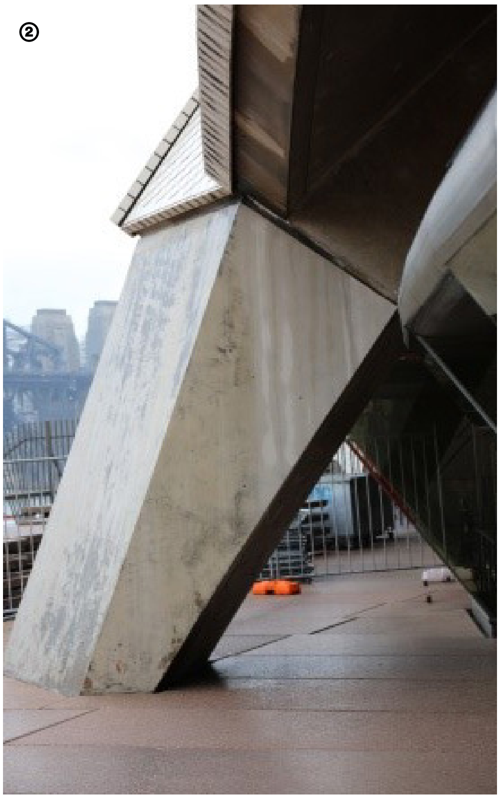
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④

The main focus on the pedestal work in the project was devoted to reducing the amount of rain running on the pedestals. The project team experimented with the installation of prototype water deviators.

A set of prototype water deviators was placed at the corner between the back and side faces of the pedestals at the level of the re-entrant joint. A 3D model of the pedestal's corner detail was created in the University of Sydney laboratory to evaluate the effectiveness of different water deviators without interfering with the Opera House structure.

① ② Degradation of pedestals over front and side surfaces

③ ④ Degradation of pedestals over back surfaces after rain

⑤ Selected corner part of pedestal reproduced with 3D printing

⑥ 3D printed detail at corner between back and side faces

OBSERVATIONS DURING RAIN

The initial scope of work changed after the project team witnessed heavy rain during an inspection on site. This represented a wonderful opportunity to document some of the problems produced by rain that had not been documented in previous reports and inspections.

The attention that had been placed on the back face of the pedestal was moved to the entire pedestal, because it was noted that a large quantity of rainwater was flowing through a gap between the edge tiles.

It was observed that by simply closing this gap, the amount of rain reaching the side and back surfaces of the pedestals would significantly decrease. It was also noted that the geometry and surface of the edge tiles caused the rain flow to be redirected inwards.

After consulting with Architect Jan Utzon and Heritage Architect Alan Croker, the scope of investigation was broadened to include:

- Installing sheeting over the concrete surfaces – e.g. bronze
- Use of protective membranes on the surface of the pedestals
- Use of re-alkalisation treatments on the concrete
- Use of water deviators installed at the location of the edge tiles
- "Do nothing" approach.

It was agreed that there will likely be a need to apply a number of solutions, as each of the pedestals has a different location and geometry, and is influenced by different weather conditions.

CLOSING THE GAP IN EDGE TILES

Trial detail for the closure of the gap between the edge tiles.

① - ④ Rain flow through gap between edge tiles

⑤ Current water flow during heavy rain

⑥ Before trial

⑦ After installation of tile component to close gap between the edge tiles

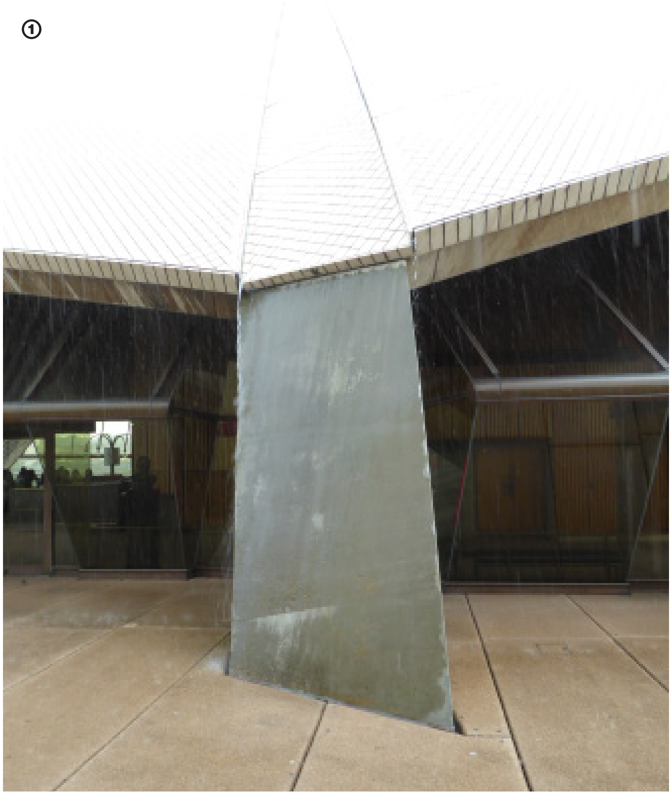
During these inspections it was observed that the entire perimeter of the sails needed further investigation during rain activities. These inspections continue whenever rain opportunities arise and will assist in identifying areas where high rain flows occur, and potential locations of water infiltration. Prototype water deviators were installed near the edge tiles and these are being monitored to assist in developing possible solutions.

① Overview of the pedestal with rain flow

② Close-up of fountain effect produced by the rain

③ Trial solution

④ Testing of trial solution with water flow produced with fire hoses



Northern Broadwalk Investigations

While extensive inspection and repair works have been carried out on the Northern Broadwalk before the comprehensive study in August 2015, the records of these activities were limited. Site visits performed by the University of Sydney team in August / September 2015 visually inspected selected beams and columns to provide a framework for monitoring and documenting typical structural elements in this area.

This was not further pursued by the University team once it was identified that Arup had established a similar framework for their regular inspections.

⑤ Site visit of part of the project team
(left to right: Dean Jakubowski, Jan Utzon, Kerry Ross, Alan Croker, Professor Gianluca Ranzi)

DEVELOPING A CONCRETE CONSERVATION FRAMEWORK PART 3:

The project team developed a concrete classification system, based on AS 3600-2009 Concrete Structures. The system provides a Concrete Exposure Classification system with surface exposure condition descriptions ranging from A1 (completely protected) to C2 (in seawater within a tidal zone).

Drawing on the history of the building, existing documentation, systems, records and policies enable a consistent set of parameters to be identified for classification purposes and subsequently implemented in the Concrete Conservation Framework.

The essential parameters for the Opera House classification system are:

ASSET IDENTIFICATION

- Location
- System
- Asset
- Surface
- Protective System

ASSET PROPERTIES

- Access
- Structural Role
- Exposure of Asset
- Exposure of Protective System
- Level of Significance
- Tolerance for Change

PROTECTIVE SYSTEM PROPERTIES

- Type of system
- Level of Significance
- Tolerance for Change

The Concrete Conservation Framework was developed in parallel with and to be compatible with the Opera House Building Information Model. To develop the framework for the Building Information Model, the Opera House partnered with international experts in the field – AECOM (Australia), BIM Academy (UK) and EcoDomus (USA).

This partnership helped to align the Concrete Conservation Framework with the Building Information Model, and also continues to develop new technology solutions to support the planned future automation of aspects of the Concrete Conservation process.

Advanced modelling and post-processing approaches are used to evaluate the structural conditions and levels of degradation. Repair strategies must comply with the concrete conservation principles of the Opera House Conservation Management Plan. Specific repairs will draw heavily on previous construction techniques, historic knowledge of Opera House staff and recent technical advancements.

The effectiveness of repair strategies will be evaluated in a controlled laboratory environment, before being considered and assessed for possible use on the Opera House. Once a repair procedure is deemed to satisfy concrete conservation and durability requirements, a repair protocol is to be specified for use on the Opera House building. The effectiveness of a repair can then be evaluated over time.

Full details of the proposed Concrete Conservation Framework are included in **Appendix A**.

CAPTURING HISTORY

REPOSITORY OF KNOWLEDGE

The Repository of Knowledge is a searchable database, created to consolidate existing and new reports, databases and historical information gathered from various sources. It includes interactions with people who have been involved with the building throughout its history, and storage of the oral histories recorded during the project.

During the Critical Analysis projects, students researched historical reports and other available information, which was added to existing information being stored in the Building Information Model. The main challenge encountered during this review was the limited information available on inspections and maintenance activities carried out in the past. Students were able to comment on the structure's condition at particular points in time, but without necessarily having the ability to place these activities within the overall timeline of the building's life.

As a result of the students' work, a comprehensive search for past documentation and reports was initiated and led by the Opera House during the last stage of the project.

Many Arup individuals from around the world have been involved in Opera House projects – forming an unparalleled organisational body of knowledge in the form of project records, archival materials and individual experiences. This information is now being brought into the Opera House's Repository of Knowledge.

Keeping up with Change

The structural engineering of the Opera House becomes increasingly more complex over time as it is progressively altered to accommodate modifications, upgrades and renewal projects, which are necessary to maintain the place as a functional public building and leading performing arts centre.

In order to understand in detail the existing structure of any part of the building it is necessary to consult the structural drawings. Ideally these would be 'as-built' construction drawings, which have been annotated to show significant changes from the design shown on the construction drawing. The Opera House's 'as-built' drawings are not a complete 'as-built' record and often 'as-built' drawings do not exist.

Some areas are virtually unchanged (such as the roof sails), whereas others (such as the Western Foyers) have changed considerably and on many occasions. The easiest and fastest way to determine what modifications affect a particular area is by consulting those people who have built up knowledge of the Opera House structure over a considerable period of time, through participation in the original construction, various modifications and upgrade projects. However, access to information in this way will not always be possible, so a consolidated body of knowledge contained in the Repository of Knowledge is critical to the long term survival of this information.

Improving Knowledge Management

Developments in technology have introduced new hardware, software and communication technology, which has progressively changed the way work is carried out and archived. Records range from hardcopy, microfilms and microfiche, to digital entries, leading to a lack of universal archive.

Keeping track of accumulated knowledge over a long period of time is challenging, since archive systems are not designed for efficient retrieval of information, especially where essentially the same project has been running intermittently for nearly 60 years.

As result of the Concrete Conservation Project, the considerable value of the knowledge of past projects held in Arup and Opera House archives, and retained in the memories of current and retired staff is now being captured in a single location, along with the importance of passing on this knowledge to future generations.

Communicating Knowledge

The project steering committee met regularly throughout the project to share information and ideas, and support the project team with expert advice and guidance. Progress was also reported to the Sydney Opera House Conservation Council at their regular meetings.

In June 2016, the Opera House hosted one of the Australia ICOMOS, DOCOMOMO Australia, NSW Chapter AIA Sydney Talks Series in the Opera House Utzon Room. The subject of the talk was 'Keeping it Modern: The Sydney Opera House Concrete Conservation Strategy'. The proposed Concrete Conservation Framework was presented to an interested and engaged audience of conservation specialists.

In July 2016, at the invitation of the Getty Foundation, Greg McTaggart, Sydney Opera House Director, Building (now retired) attended the 'Keeping It Modern' workshop in London, UK. Greg delivered three presentations on the subjects of Sydney Opera House Concrete Conservation and the Conservation Management Plan 4th Edition (published November 2017). Greg also participated in a panel discussion at the conference.

Steering committee members, Sheridan Burke and Gianluca Ranzi also attended the conference in London. Sheridan (joint with Susan Macdonald) presented 'Securing good conservation outcomes for modern Heritage: the role of conservation plans and other methodologies in the preservation process'. Sheridan lectures in all the Getty Foundation's annual workshops on the topic of conservation planning.

Gianluca (joint with Greg McTaggart) presented ' Sydney Opera House Concrete Conservation Project'.

The response to the presentations was overwhelmingly positive.

① Engineering and Heritage students during a site visit

② Steering Committee meeting

③ Beatriz Lee, Sydney Opera House Building Strategy & Documentation Specialist presenting the proposed Concrete Conservation Framework to ICOMOS Australia members in the Opera House Utzon Room, June 2016

OUR STORIES

Sydney Opera House is in a unique position for a World Heritage listed site. As one of only two cultural sites to be listed during the lifetime of its architect, the site has a rare opportunity to benefit from first hand accounts of its design and construction.

The project team set out to capture the knowledge held in the memories of the workers who contributed to the creation of the Opera House, and others who have played a significant role in the life of the building since it opened.

Contact was made with as many of these experts as possible, many of whom had retired, and the team discovered that all were keen to participate and share their recollections.

The initiative to capture these vital historical records aimed to:

- collect a comprehensive set of data, information and knowledge that had not previously been available in reports and other documents
- identify and locate key reports and documents not readily available through the existing Opera House document control system
- gain insight into the experts' knowledge of the Opera House structural conditions, location of potential critical areas of risk and previous repairs

The Arup 'Originals'

Sydney Opera House was a project with such extreme technical challenges, where the design and construction took place over an extended period and which, for the entire period, was played out under a public and political spotlight.

Dr John Nutt AM and Ian MacKenzie were two young structural engineers who played a significant role in the construction of the Opera House. Dr John Nutt was among the first in the world to apply the use of computers to building design. He went on to become Chairman and CEO of the Arup Australasian practice, and a member of the Sydney Opera House Conservation Council, now retired.

Ian MacKenzie, who was Resident Engineer on the Opera House site for Stages 1 and 2 of construction (1959 – 1967) and led the structural design for Stage 3 (1967 – 1973), also become a Director of the Arup Australasian practice. He was closely involved in the many Opera House investigations, repairs and modifications carried out until his retirement.

Ron Bergin, another retired Arup Australasian Director was a Surveyor during Stage 2 of construction (which included the roof sails). He was instrumental in achieving the complex setting out for the roof construction, using the application of early computer technology.

Dr John Nutt, Ian MacKenzie and Ron Bergin, voluntarily participated in the project by providing information and advice, participating in workshops and events, and recording their oral histories. Their contribution was of invaluable assistance in the project, and continues to be through their ongoing relationship with the Opera House Concrete Conservation team.

The project team recorded interviews with several other individuals who have played a key role in either the construction of the Opera House, or in its care and maintenance:

Malcolm Brady	NSW Department of Public Works engineer on the 1990s Opera House sails upgrade project (retired)
Alan Croker	Consultant Heritage Architect to Sydney Opera House (2003 – present), author of the Sydney Opera House Conservation Management Plan 4th Edition (2017)
John Dare	NSW Department of Public Works engineer on the 1990s Opera House sails upgrade project, later worked in the Sydney Opera House Building Development team (retired)
Ray Dick	Sydney Opera House Contracts Manager (1988 – present) brought considerable knowledge in locating reports and documents on condition assessments, repairs, potential areas of risk and related structural information.
Colin Ging	Director, Savills Project Management, Strategic Advisor to Sydney Opera House for the Utzon Room (2004), Colonnade (2006), Accessibility & Western Foyers (2009), and Vehicle Access & Pedestrian Safety (2015) projects (retired)
Dean Jakubowski	Sydney Opera House Building Operations Manager (2006– present) recorded his knowledge of the structure, challenges in today's maintenance operations and potential areas of risk
John Kuner	Worked on the Opera House construction 1963 – 1967
David Moorehead	Arup engineer (current)
Malcolm Nicklin	Macdonald Wagner & Priddle Coordinating Civil Engineer
John Reid	Former Director of Blue Strand Industries
Steve Tsoukalas	Employed on the Opera House site for 50 years from 1968 - 2018, working at first on construction of the building, then for various maintenance contractors. Instrumental in developing sustainable cleaning methods, including the use of bicarbonate of soda to clean concrete and olive oil to maintain the bronze in the Opera House
Jan Utzon	Architect, member of Sydney Opera House Eminent Architects Panel, son of Opera House Architect Jørn Utzon

ARUP TEAM

Current members of the Arup team were also interviewed to record their detailed knowledge on the Opera House structure; their historic memory related to repairs and potential areas of risk; and gain insight into the modelling of the structure to inform the definition of the concrete monitoring framework.

Building the Stories

After initial recordings of oral histories were completed with these key individuals, the project team organised joint recording sessions with the experts who had worked on the construction of the Opera House, noting that the memories of one person often triggered more stories from another. The joint sessions proved fruitful in piecing together far more detailed recollections than could be achieved in individual interviews.

The enormous challenges faced during the design and construction of this masterpiece without precedent required extraordinary focus and dedication from all members of the design and construction teams over many years. As each expert account of these challenges was recorded, a common theme emerged that sparked interest in the project team.

The consistent message coming through was that the spouses of the construction team played a critical role in supporting these workers in the successful completion of the Opera House. Many of the experts expressed that their contributions would not have been possible without the support of their partners at home.

The project team organised another meeting, inviting the spouses to participate in an informal brunch, at which their stories were recorded. Not only did the event reunite former work colleagues and their partners after some 40 years, but the Opera House also captured a greater depth of stories than could have been imagined when the project began.

Conserving a Masterpiece

The project team engaged Versus Media to produce a 3-minute video on concrete conservation at the Sydney Opera House. The video gave an overview of the Opera House's research on the Concrete Conservation Project in partnership with Getty Foundation, Arup and University of Sydney.

The video highlighted the Opera House as a foremost example of innovative use of concrete in the 20th century, how it's built, and how it can be conserved for future generations through developing robust systems and non-invasive techniques to monitor concrete. The video included footage of the Arup 'Originals', current and former staff from Sydney Opera House and Arup, students, technical staff and academics from University of Sydney.

The craftsmanship demonstrated in past patch repairs carried out in areas of the pedestals and on the tile lids will be useful in informing future repair strategies. It was important to document this information in a visual medium so that the techniques could be demonstrated to assist in training the next generation of trades staff.

The video can be viewed at the **Opera House website**.

① Malcolm and Marjorie Nicklin

② Dr John Nutt AM

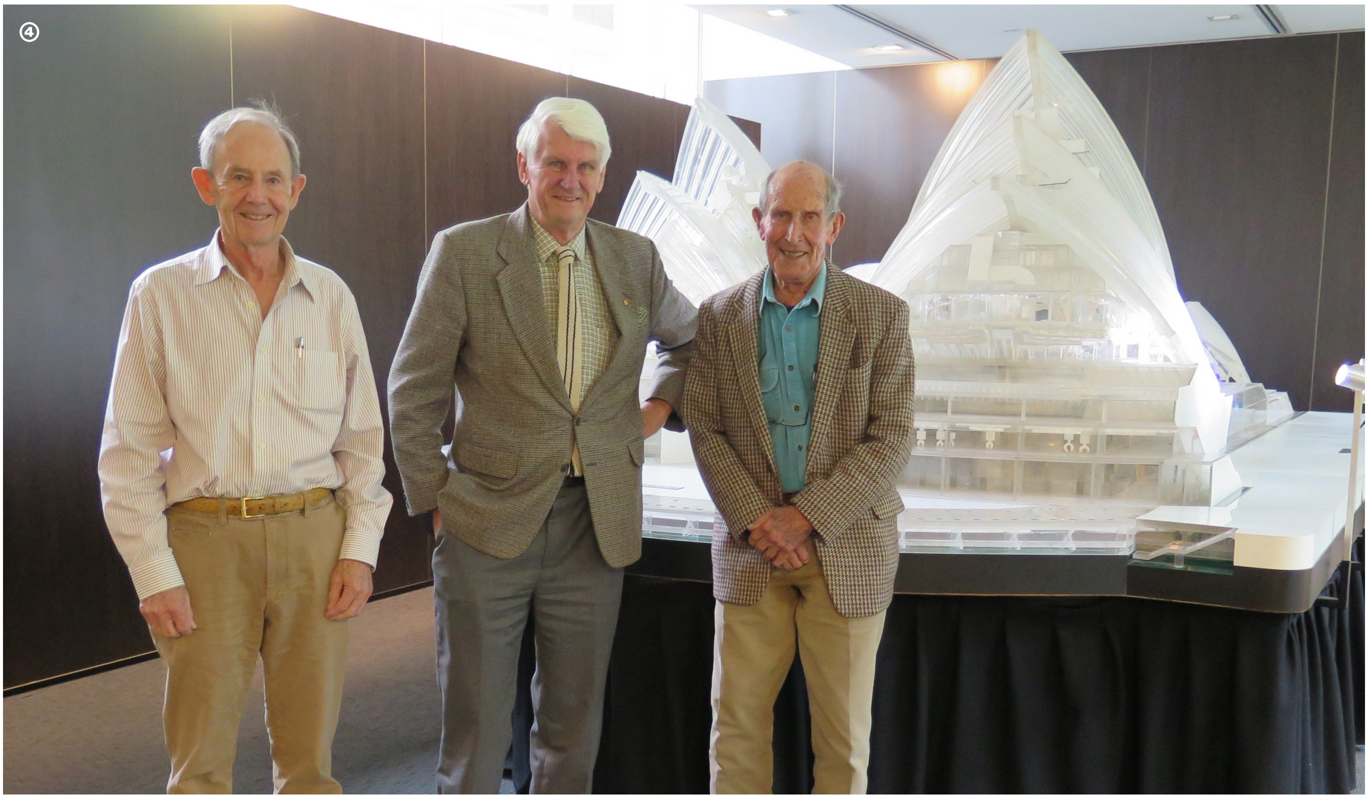
③ Ian and Anne MacKenzie

④ John Kuner, Dr John Nutt AM, John Reid


①


②


③


④

Chapter 3

NEXT STEPS

CONCRETE CONSERVATION FRAMEWORK IMPLEMENTATION

In the two years since that project concluded, the Opera House and its partners have continued in the study of concrete conservation and development of condition monitoring techniques. The team continues to work at the leading edge of technology in the field and is working with industry and academic experts to develop the systems in line with the vision for what is possible.

Condition Monitoring

Advancements in technology have provided innovative options to proactively monitor concrete. The roof tiles and concrete chevron tile lid structures have the highest surface exposure to the elements. Conserving their integrity will inevitably conserve the concrete elements that they protect: the ribs.

Several outcomes of the Concrete Conservation Project have facilitated the progression of the Concrete Conservation Framework:

- exposure to a range of inspection techniques using established and emerging technologies
- ongoing engagement with the "Arup Originals" and other experts in concrete, such as current Arup staff and the University of Sydney Centre for Advanced Structural Engineering
- recognising that it is essential to monitor and categorise concrete condition to determine how to proceed with its conservation
- application of Building Information Management technology for data storage and analysis

The Opera House has continued to develop a systematic condition monitoring methodology that is cost effective, efficient and sustainable. This will enable the development of a robust conservation strategy that works towards heritage objectives, while minimising lifecycle cost and forecasting forward estimating costs.

A new condition auditing tool is under development and aimed for deployment in 2019. The first iteration will focus on cleaning inspections, but as the technology is refined, it will also be used to monitor the condition of concrete, and potentially other building fabric such as timber and granite.

Concrete Inspections

The team continues to explore a range of inspection techniques to check for any degradation of the concrete. Non-invasive techniques are being explored to the extent possible so as to avoid impact to heritage fabric. Monitoring techniques may include:

- systematic building rainfall inspections
- internal borescope inspections
- tomographic inspections
- analysis of sail and podium stormwater drainage performance
- structural waterproof membrane inspections
- aerial drone high resolution and infrared inspections

Aerial drone high resolution and thermographic machine learning inspections offer an exponential increase of data capture, allowing a greater level of analysis to be recorded in the Building Information Model.

The drone carries sensors and cameras capable of monitoring:

- tile adhesion
- tile cracking deterioration
- organic growth
- tile to tile grout erosion
- lid to lid sealant failure
- rainwater leak detection

It is anticipated that the subsequent machine learning analysis of the data will be displayed in the Building Information Model as a series of hot spots across the structure.

To complement drone inspections, collaboration with the University of Sydney Centre for Advanced Structural Engineering has resulted in the development of an augmented reality platform for tile tapping. Building on the work done during the Concrete Conservation Project, this scientific method efficiently and reliably tests for drumminess (hollow sound) in the roof tiles, while providing automated locational references and condition assessment information into the Building Information Model. The results of this testing method can be used to improve efficiency and reliability of tile tap tests and to verify drone testing results.

Tile sealants and grouting

Rainy day inspections have identified a risk of sealant failure in some areas, and localised repairs have been undertaken to address rainwater leaks.

Subsequent drone, infrared and visual aerial drone leak detection inspections have been trialled and will target subsequent borescope investigations. These will inform the development of a cost-effective and efficient monitoring and repair strategy.

Broadwalk Remediation

In 2017, Arup completed further structural condition inspections on the Northern Broadwalk. This found that localised concrete repair is unlikely to materially increase the service life of the concrete structure, and more extensive works will be needed as the structure approaches its life expectancy.

Monitoring continues on all the Broadwalk structures, with localised repairs made when necessary.

Continued Collaboration with External Experts

Since the project was completed, these experts who provided oral histories during the project have continued to participate in the formation of the Concrete Conservation Consultation Group, which meets with Opera House management twice a year to continue progress on concrete conservation.

Sustained engagement with experts that have specialist knowledge of the building and of concrete will continue in the long term, as the Opera House determines how best to approach its conservation framework.

Through the accumulation and application of this knowledge, and regular collaboration with experts in the field, in-house subject matter expertise also is being developed in the conservation of concrete post-tensioned structures.

This knowledge will continue to be shared with other building owners and interested parties, through this report, presentation of papers and direct collaboration with other asset owners.

Use of Building Information Modelling Technology

The Opera House has been developing its Building Information Model system for several years. The system has been configured to record the concrete condition, testing and treatment history for all building elements. Various complementary monitoring techniques will be applied to testing the same qualities in the roof sails and podium.

For the first time, all data on concrete will be centrally located within Building Information Model. The system can be used as a platform for data analysis and extrapolation, to develop models that inform concrete conservation actions such as concrete condition and remediation models, materials life prediction models, and structural life prediction models.

These models can facilitate the development of concrete maintenance plans that enable systematic and targeted conservation.

CREDITS

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DEFINING THE PROJECT SCOPE & GRANT APPLICATION DEVELOPMENT

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CREDIT	PAGE
Arup	19 (top left), 22 (right), 30, 31 (middle), 44 (left)
Conservation Management Plan 4th Edition	28, 29, 86, 97, 88
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Mitchell Library, State Library of New South Wales, Courtesy Max Dupain & Associates and Jill White	23 (right)
Sydney Opera House staff	23 (left), 24, 31 (top left, top right, bottom left and bottom right), 38, 47, 50, 51, 52, 55 (top), 63 (bottom), 84, 85, 89, 91, 92, 93, 95, 96, 97, 98, 99, 100, 101, 102, 103, 105, 106, 107, 108, 109
Sourced by John Dare	25 (bottom)
The 'Originals' scanned content	19 (top right)
The University of Sydney	41, 42, 43, 44 (right), 45, 46, 48, 49, 53, 59 (top)
Versus Media	56, 59 (middle and bottom), 63 (top, middle left and middle right), 70

APPENDIX A

CONCRETE CONSERVATION FRAMEWORK

CONSERVATION PRINCIPLES

Determine conservation principles based on corporate goals in consultation with Conservation Council.

Background

The Sydney Opera House Conservation Management Plan 4th Edition is the primary reference document for the conservation principles used in the Concrete Conservation Framework.

The Conservation Management Plan is one of the chief guiding documents on matters relating to the conservation and management of the significant values of the Sydney Opera House. The Conservation Management Plan sets out how to retain significance in relation to Utzon's principles, and how to implement and manage change.

The Conservation Management Plan provides the following as guiding principles, based on the **Burra Charter** approach to conservation:

- Cautious approach to change, where the fundamental principle in any approach to change should be to change 'as much as necessary but as little as possible'
- Testing the minimum option first, where 'the minimum options should be considered and tested, and only if these do not work should options that involve greater change be considered or pursued'

Methodology

LEVEL OF SIGNIFICANCE

The level of significance of a concrete asset is considered when determining its appropriate inspection, testing and maintenance principles.

The Conservation Management Plan assigns a level of significance to each location of Sydney Opera House. Elements found in these locations are assigned the same level of significance. Concrete assets are assigned their level of significance based on this grading system.

Definitions of these levels are as follows:

A Exceptional significance

These elements are essential to the significance of the place. They play a crucial role in supporting this significance.

B High significance

These elements are of high significance. They play an important but not necessarily crucial role in supporting the significance of the place.

C Moderate significance

These elements are of moderate significance and provide support to elements or functions of higher significance. They play a role in supporting the significance of the place, but may be inadequate in their current configuration or use.

D Low significance

These elements are of low significance. They play a minor role in supporting the significance of the place, or may have been compromised by later changes.

Intrusive

Relates to an item or component that obscures, impedes, diminishes or otherwise damages the significance of an element or its component parts.

TOLERANCE FOR CHANGE

The Tolerance for Change of a concrete element is considered when determining its appropriate testing and maintenance principles.

The Conservation Management Plan assigns a sensitivity to change score for each element in Sydney Opera House with respect to function, form, fabric and location.

Concrete elements can be scored in this context as follows:

1 Low Tolerance for Change

2 Moderate Tolerance for Change

3 High Tolerance for Change

CONCRETE CLASSIFICATION

Create concrete classification system of Sydney Opera House concrete

Background

The initial process undertaken in the development of the Concrete Conservation Framework was to research what information existed in relation to concrete generally. The research more specifically targeted documentation around classification of concrete, management methods previously employed or research into the subject matter that may exist and could be drawn on to provide standardisation for the Framework.

The research looked at:

- **Internal to Sydney Opera House**
  - o established plans and strategies
  - o existing categorisation systems
  - o reports and surveys
  - o history of repairs
- **External sources**
  - o Standards or specifications
  - o Heritage reference standards
  - o Terminology standards
  - o Systematic approaches
- **Industry Resources**
  - o Engineers
  - o Academics
  - o Other knowledgeable sources.

The outcome of this investigation resulted in a wealth of documentation that could be drawn upon to create the strategy and in particular the classification system specific to the Opera House.

The following documents, in order of importance to the development of the strategy, were drawn upon:

- Sydney Opera House Conservation Management Plan 4th Edition
- The Burra Charter 2013
- AS 3600-2009 Concrete Structures
- Conserving Concrete Heritage Experts Meeting - 2014
- NARA + 20 – Heritage Practices, Cultural Values and the Concept of Authenticity
  - o CS TR 54 - Diagnosis of Deterioration in Concrete Structures
  - o ARUP – SOH Maintenance Manual (circa 1973) – Outlines maintenance practises for concrete, tiles and glass
  - o ARUP reports – SOH Pre-cast Panel inspections
- Concrete Institute of Australia
  - o Z7/01 Durability Planning
  - o Z7/05 Durability Modelling of Reinforcement Corrosion in Concrete Structures
  - o Z7/07 Performance Tests to asses Concrete Durability

The following secondary documents have been referenced in the development of the entire conservation life cycle strategy:

REF CODE	TITLE
	Concrete Repair Manual: Fourth Edition 2013 CD/Book Pack
ACI 365.1R-00	Service-Life Prediction
ACI 364.1R-07	Guide for Evaluation of Concrete Structures before Rehabilitation
ACI 201.1R-08	Guide for Conducting a Visual Inspection of Concrete in Service
ACI 546.2R-10	Guide to Underwater Repair of Concrete
Condition Evaluation	
ACI 201.1R-08	Guide for Conducting a Visual Inspection of Concrete in Service
ACI 210.4-2009	Guide for Non-destructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures
ACI 364.1R-07	Guide for Evaluation of Concrete Structures before Rehabilitation
CS TR 54	Diagnosis of Deterioration in Concrete Structures
BRE Digest 444	Corrosion of Steel in Concrete Part 1: Durability of Reinforced Concrete Structures
BRE Digest 444	Corrosion of Steel in Concrete Part 2: Investigation and Assessment
BRE Digest 434	Corrosion of Reinforcement in Concrete: Electrochemical Monitoring
ACI 228.2R-98	Non-destructive Test Methods for Evaluation of Concrete in Structures
CS TR 60	Electrochemical Tests for Reinforcement Corrosion
ACI 224.1R-07	Causes, Evaluation and Repair of Cracks in Concrete Structures
CS TR 22-Fourth Edition	Non-Structural Cracks in Concrete
ACI 364.9T-03(11)	Cracks in a Repair
Concrete Restoration	
ACI 546R-04	Concrete Repair Guide

Abbreviations:

ACI = American Concrete Institute
BRE = British Research Establishment
ICRI = International Concrete Repair Institute

REMR = Repair Evaluation Maintenance Rehabilitation
CRM = Concrete Repair Manual
CRM1-23 = Concrete Repair Manual Volume 1, page 23.

REF CODE	TITLE
Materials for Repair	
Guideline No. 320.2R-2009	Guide for Selecting and Specifying Materials for Repair of Concrete Surfaces
ACI 546.3R-06	Guide for the Selection of Materials for the Repair of Concrete
Preparation	
Guideline No. 310.1R-2008	Guide for Surface Preparation for the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion
ACI 364.6T-02	Concrete Removal in Repairs Involving Corroded Reinforcing Steel
ACI 364.7T-02	Evaluation and Minimization of Bruising (Microcracking) in Concrete Repair
Application Methods	
Guideline No. 320.1R-1996	Guide for Selecting Application Methods for the Repair of Concrete Surfaces
Protection	
CS TR 50	Guide to Surface Treatments for Protection and Enhancement of Concrete
Surface Preparation	
CS-MR-4.4	Cleaning Concrete Surfaces
CS-MR-4.3	Removal and Prevention of Efflorescence on Concrete and Masonry Building Surfaces
Corrosion Management	
BRE Digest 444	Corrosion of Steel in Concrete - Part 3: Protection and Remediation
CS TR 36	Cathodic Protection of Reinforced Concrete
CS TR 37	Model Specification for Cathodic Protection of Reinforced Concrete
NACE Standard RP0390-2006	Maintenance and Rehabilitation Considerations for Corrosion Control of Atmospherically Exposed Existing Steel-Reinforced Concrete Structures
Special Cases	
ACI 546.2R-10	Guide to Underwater Repair of Concrete

Principles

1 Develop a system that links to current standards or specifications

2 Ensure the system aligns with existing Sydney Opera House strategies and plans

3 Simple to understand and deploy

Methodology

Drawing on the history of the building, existing documentation, systems, records and policies enables a consistent set of parameters to be identified for classification purposes and s ubsequently implemented in the Concrete Conservation Framework.

The essential parameters for the Opera House classification system are:

ASSET IDENTIFICATION:

- Location
- System
- Asset
- Surface
- Protective System

ASSET PROPERTIES:

- Access
- Structural Role
- Exposure of Asset
- Exposure of Protective System
- Level of Significance
- Tolerance for Change

PROTECTIVE SYSTEM PROPERTIES:

- Type of system
- Level of Significance
- Tolerance for Change

To enable the setting of parameters, an asset identification system is created that identifies each piece or section of concrete as individual **assets**. This enables a database to be created for recording relevant data about each asset whilst also enabling the grouping of like assets that are exposed to similar environmental conditions into **systems** which will provide reference

1 Asset Identification (tag)

STRATEGY STEP	ITEM	DESCRIPTION
1 **Identify asset and surface** 1.1 Location	Location	Where is the Asset located? **Room Number**
1.2 System	System	Which **group of concrete assets** is this asset a part of? **Assets** with similar properties and materials can be grouped into a **System**
1.3 Asset	Asset	Which **concrete asset** is being assessed? This includes a description of its materials
1.4 Surface	Surface	**Which side** of the asset is being referred to? (e.g. a clumn has four sides)
1.5 Protective system	Protective System	Protective system adhered to surface being assessed, such as paint, tiles, silicone, waterproof membrane, cathodic protection Does it exist for this asset?

material to carry out performance analysis at a later date.

For detailed analysis to occur, it is essential that all concrete sections are identified as individual assets. As part of this identification, it should also be established if the concrete asset has a protective system or layer installed.

Five categories have been established to capture the relevant information for the identification tag as follows:

LOCATION

The Opera House was originally designed with a very detailed rooms and doors naming convention that was applied to all plans and documentation produced at the time of construction. This system has been maintained and it now the source of truth for every space on the site.

SYSTEM

A group of assets with like properties and environmental conditions. A small sample of concrete assets or group of assets are detailed in the table below which are drawn from the body of the Conservation Management Plan for the basic description of the assets and general location.

ASSET

The individual item or length of concrete that can be treated or rebuilt as a single stand-alone piece.

SURFACE

Any 3 dimensional object has more than 1 side. A rectilinear piece of concrete, for example, has 6 surfaces. Each of these could be exposed to different environmental conditions and hence require a different treatment or analysis.

PROTECTIVE SYSTEM

Some assets have a protective coating. For example, this protective coating could be a bitumen membrane applied with heat; ceramic tiles adhered to the concrete at time of construction, cathodic protection system embedded under the surface of the assets or a simple painted surface. The types of protective system are varied but all have the same intent, to protect the underlying asset from the environment.

CONSERVATION MANAGEMENT PLAN DETAIL

Roof shells	
Roof shells	Glazed tiles
Roof shells	Tile lids
Roof shells	Concrete ribs assembled from prefabricated elements
Podium exterior	
Podium exterior	Pre-cast granite cladding and paving
Podium exterior	Projecting pre-cast granite hoods over openings
Podium exterior	Access steps and balconies with solid pre-cast granite balustrades
Podium exterior	Western colonade structure of unpainted concrete and pre-cast

2 Asset Properties

The properties of the asset guide the strategy through the physical process of inspection and repair. They provide insight into the interaction of the variable properties that all have a bearing on the final solution for each individual asset.

ACCESS

A visual inspection is the preferred first level method to determine the condition of a concrete asset, enabling a quick understanding of the general condition of the asset. To conduct a visual inspection, the primary determinant for the type of inspection that can be conducted is access to the surface of the asset.

- Can it be accessed without special equipment?
- Can it be accessed without disrupting its protective system?
- Is it under a tile or a waterproof membrane?

Outcome **Accessible** or **Inaccessible**

Not all assets can be examined by a visual inspection. However, if the asset is important enough, it may warrant inspection through non-visual means to determine what might be occurring under the surface. The outcome of Inaccessible leads to a range of options that will be suitable for different types of assets and surfaces. These are reviewed later in the strategy.

STRUCTURAL ROLE

The asset's structural role, **load bearing, non-load bearing or cladding**, is one of the key determinants for priority and type of inspection. The load bearing or structurally supportive assets will require much closer attention, as structural failure is not an acceptable option. The structural role can be assessed by conducting a risk profile assessment informed by structural engiwneering input and construction documentation.

STRATEGY STEP	ITEM	DESCRIPTION
2 **Determine Asset properties** 2.1 Access	Access	Can the asset be accessed without special equipment? Can the asset be accessed without disrupting its protection? **Accessible** or **Inaccessible**? Included as per advice from Arup
2.2 Structural Role	Structural Role	Load bearing, Non load bearing or Cladding Included as per advice from Arup
2.3 Exposure of Asset	Exposure of Asset	**A1** (protected), **A2, B1, B2, C1 or C2** (unprotected) Concrete Exposure Classification (AS3600) Surface Exposure Condition, included as per advice from Arup
2.4 Exposure of Protective system	Exposure of Protective system	**A1** (protected), **A2, B1, B2, C1 or C2** (unprotected) Concrete Exposure Classification (AS3600) Surface Exposure Condition, included as per advice from Arup
2.5 Level of Significance	Level of Significance	**Exceptional, High, Moderate or Low** Asset's level of significance defined by the policies of the Sydney Opera House Conservation Management Plan
2.6 Tolerance for Change	Tolerance for Change	**Low, Moderate or High** for each attribute: **Function, Form, Fabric and Location** Asset's Tolerance for Change defined by the policies of the Sydney Opera House Conservation Management Plan

EXPOSURE OF ASSET

The environment to which the material is exposed is a key determinant of the type and timing of inspection, repair and replacement that would be considered. AS 3600 Australian Standard for Concrete Structures contains a Concrete Exposure Classification system with Surface Exposure Condition descriptions which have been adopted in this strategy.

Classification and Exposure Condition descriptions range from A1 (completely protected) to C2 (seawater within a tidal zone).

EXPOSURE OF PROTECTIVE SYSTEM

Similarly, we are using the AS 3600 Concrete Exposure Classification system to describe the protective system for each asset.

For a concrete surface with a fully functioning protective system, the assumption can be made that the surface is completely protected, i.e., it falls under the A1 exposure classification and the highest level of protection. This affects inspection frequencies and types of repair that may be considered for the asset.

If the protective system is not functioning, i.e. it has a split or penetration through its layers that allows the environment to reach the asset's surface, this activates an entire sub process in the strategy.

It requires the downgrading of the exposure classification of the surface that is no longer being protected, and the adjustment of future actions accordingly.

A1	Completely protected
A2	Interior: Fully enclosed In contact with ground: Non-aggressive soils / Above high water level
B1	Interior: Repeated wetting / drying
B2	Exterior: Above ground In seawater: Permanently submerged In contact with ground: Below lowest astronomical tid
C1	In seawater: Spray zone
C2	In seawater: Tidal / splash zone

LEVEL OF SIGNIFICANCE

Each of the main elements of the Sydney Opera House has been assessed for its individual significance relative to the exceptional significance of the whole place, and includes consideration of both tangible and intangible values.

All elements are to be maintained, used and managed in accordance with their relative level of significance.

The higher the significance, the greater the level of care and consideration required in determining any decision or action which may affect it, the objective being to ensure that any work, whether it be temporary or permanent, will reinforce and not reduce, the identified significance. It is one of our key heritage indicators.

SIGNIFICANCE RANKING, SUMMARY DESCRIPTION AND SIGNIFICANCE VALUES OF ELEMENT

ATTRIBUTES OF EACH COMPONENT

Tolerance for Change

element:
Roof shells externally

significance ranking **A**

Three groupings of soaring, curved, concrete framed roof shells, clad with white ceramic tiled lid panels, surmounted by fine curved bronze lightning rails and infilled by glass walls

Tolerance for Change
1 = Low tolerance
2 = Moderate tolerance
3 = High tolerance

Further Considerations
(to be read in conjunction with the relevant policy section for each element)

selected components:	Form	Fabric	Function	Location	Further Considerations
Glazed tiles	1	1	1	1	Maintenance with replacement only where necessary. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.10.
Tile lids	1	1	1	1	Maintenance with replacement only where necessary. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.10.
Concrete ribs assembled from prefabricated elements supported on fan shaped pedestals	1	1	1	1	Maintenance only. Monitoring required to ensure structural integrity and finish are maintained. Refer to discussion and policies in Sections 4.7.2, 4.18.1, 4.18.2 and 4.18.3. Preservation treatment may be required to protect pedestals in accordance with Policies 4.6, 7.2, 18.6, 18.7 and 18.8. Refer to intrusive items below.
Lightning rails – stainless steel	1	1	1	1	Materials and configuration are most important. Refer to discussion and policies in Section 4.7.2.
Deeply recessed bronze louvre walls infilling spaces between shell ends	2	1	2	1	Repeated and standardised bronze components geometrically arranged to complement the ribbed structure are most important factors. Refer to discussion and policies in Section 4.7.3.
Glass walls and supporting structures	2	2	1	1	Maintain as existing unless 'Major change' applies. Minor modifications permitted in accordance with Policy 4.4. Refer to discussion and policies in Section 4.7.3.
Shell uplighting at base of end pedestals (north and south)	3	3	2	1	Refer to discussion and policies in Section 4.14 *Lighting*.
Recent surface treatment of concrete pedestals externally	**Intrusive**				Explore less intrusive means of managing concrete deterioration, and protecting and exposing original surface – refer to Section 4.18.3 *Treatment of unpainted and precast off-form concrete*, and Policy 18.6.
Nose lights on shells	**Intrusive**				Both the fixtures and the glare are intrusive. Explore less intrusive means of lighting public space – refer to Section 4.14.2 *Lighting of Forecourt, Broadwalk and Podium (monumental) steps*.

COMPONENT NAME

'TOLERANCE FOR CHANGE' RANKINGS ACROSS THE 4 ATTRIBUTES

FURTHER CLARIFICATION OF APPLICATION OF POLICY TO REFERENCE WHERE APPLICABLE

The Conservation Management Plan identifies the heritage significance of each element and provides guidance as to the role each component plays in the overall plan. It enables the team charged with repairing any deterioration in the assets to draw on the definitions to determine what type of repair can be undertaken.

A concrete asset can be assigned levels of exceptional, high, moderate or low significance.

Level of Significance		Definition
A	Exceptional significance	These elements are essential to the significance of the place. They play a crucial role in supporting this significance.
B	High significance	These elements are of high significance. They play an important but not necessarily crucial role in supporting the significance of the place.
C	Moderate significance	These elements are of moderate significance and provide support to elements or functions of higher significance. They play a role in supporting the significance of the place, but may be inadequate in their current configuration or use.
D	Low significance	These elements are of low significance. They play a minor role in supporting the significance of the place, or may have been compromised by later changes.
Int	Intrusive	This relates to an item or component that obscures, impedes, diminishes or otherwise damages the significance of an element or its component parts.

TOLERANCE FOR CHANGE

This Conservation Management Plan table enables the user to determine if an asset has a Tolerance for Change across its Function, Form, Fabric and Location. This Tolerance for Change is considered in conjunction with the asset's Level of Significance to and in light of any repair that may be required.

It is essential to understand that the original design integrity and authenticity of the Sydney Opera House is dependent on the retention of original design. Tolerance for Change is a judgement about the 4 attributes with regard how tolerant they are to change without adverse impacts.

The Conservation Management Plan assigns each attribute of each component a low, moderate or high Tolerance for Change.

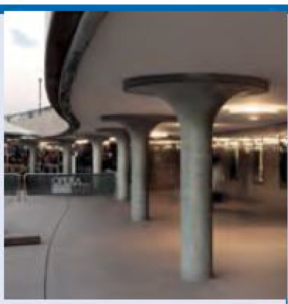
In the table below, the attribute with the lowest number (1) takes precedence over all other attributes.

In the case of the Sea Wall footpath Function is dominant attribute. Fabric and Location have a moderate Tolerance for Change. Form has a high Tolerance for Change, i.e. the visible shape or configuration could be altered if required.

element:
Lower Concourse

significance ranking **B**

Sheltered access to Sydney Opera House below western edge of Forecourt, connecting East Circular Quay with Covered Concourse and parking station, incorporating food and beverage outlets and lavatories



Tolerance for Change
1 = Low tolerance
2 = Moderate tolerance
3 = High tolerance

selected components:	Form	Fabric	Function	Location
Seawall incorporating wave guard, and continuous precast granite seating and footpath clear of all obstructions	1	1	1	1
Paving, steps and walls of solid granite	2	2	1	2
Seawall parapet of reconstituted pink granite incorporating seating bench	2	1	1	2
Seawall footpath of granite setts	3	2	1	2
Open bronze rail system to parapet edge of Forecourt revised to Jan Utzon design (completed 2010)	2	1	1	1

3 Protective System Properties

While typically, protective systems are not designed to have heritage value at the Opera House, some protective systems are intrinsic to assets of significance. As such, their heritage status needs to be considered when looking at inspection or repair.

TYPE OF SYSTEM

Detail of the system design and material make up. This information provides guidance as to the system's durability and options for repair in the event of failure.

LEVEL OF SIGNIFICANCE

In most cases, the Level of Significance is very low. Only in the case of the tiles on the roof sails does this attribute become important. In this case, the same methodology for the asset properties is employed to determine the correct actions to be undertaken.

TOLERANCE FOR CHANGE

As above, the Tolerance for Change is applied to the protective system if the asset is of significance in the Conservation Management Plan.

STRATEGY STEP	ITEM	DESCRIPTION
2 **Determine Protective systems properties** 2.7 Access 2.8 Level of Significance 2.9 Tolerance for Change	Access	Can the Protective system be accessed without special equipment? Accessible or Inaccessible?
	Level of Significance	Exceptional, High, Moderate or Low Protective system's level of significance defined by the policies of the Sydney Opera House Conservation Management Plan
	Tolerance for Change	Low, Moderate or High for each attribute: Function, Form, Fabric and Location Protective system's Tolerance for Change defined by the policies of the Sydney Opera House Conservation Management Plan

CONCRETE STRATEGY

Develop strategy and process to monitor and document condition of concrete assets

Background

The maintenance of modern concrete as a heritage building fabric that holds heritage principles at its centre is a missing piece. True to the legacy of innovation innate to Sydney Opera House this Strategy is now under development.

It was important that this strategy was not just about the Opera House, that it was applicable to the international heritage and building management community.

This strategy was shaped by every workshop and conversation throughout its development. Any version adopted for a different building will be nuanced by new needs. It is the points of divergence that defined this strategy.

As a result of these conversations it became clear early on that we had to find a way to prioritise each concrete asset, the development of a classification system became the first objective of the concrete conservation strategy. This has been discussed in the previous section.

The next component of the strategy was to monitor and document the condition of concrete assets. This section deals with this process.

Principles

Principles out of the Conservation Management Plan have been used as fundamental values of this strategy to ensure its intrinsic heritage foundation. Principles include:

- Cautious approach to change, where the fundamental principle in any approach to change should be to change ‘as much as necessary but as little as possible’
- Testing the minimum option first, where ‘the minimum options should be considered and tested, and only if these do not work should options that involve greater change be considered or pursued’
- Level of Significance; and
- Tolerance for Change

Methodology

Using the classification system as the starting point, which effectively ranks each piece of concrete according to accessibility and importance, the first decision to take is whether to inspect the asset or not.

Inspect Asset	Identity fault
For visual inspections	Cracking Chipped edge Deflection Corrosion staining Water staining Staining Corroding fixture Spall Impact damage Delamination Refer to sydney Opera House Maintenance Manualby Arup revised in accordance with current best practice for **possible defects**

1 Accessibility of Surface

If the asset's surfaces are accessible, a visual inspection can be conducted to determine the current condition.

The inspector will look for visual signs as detailed in the adjacent table.

(A score / survey tool is under development to allow the inspector to review past history of the assets and work from a photographic data base for description of the faults.)

If it is determined that all surfaces are not accessible then the asset's Level of Significance and Structural Role need to be considered before determining the next action. It is also important to consider the status or presence of a Protective System.

3. DETERMINE IF INSPECTION WILL BE CONDUTED

→ Asset Accessible → Conduct visual inspection

→ Asset Inaccessible → Consider properties of the assest

When assets or their surfaces are determined to be inaccessible for inspection, the adjacent table is used to determine the next course of action.

If an asset is determined to have Exceptional Significance and / or is of a Load bearing nature, a non-visual inspection will be carried out.

The type of inspection that may be conducted is addressed below.

3. DETERMINE IF INSPECTION WILL BE CONDUTED

→ Asset Accessible → Conduct visual inspection

→ Asset Inaccessible → Consider properties of the assest

2.2 2.5	Cladding	Non load bearing	Load bearing
Exceptional Significance	Y	Y	Y
High Significance	N	N	Y
Moderate Significance	N	N	Y
Low Significance	N	N	Y

Cladding / Non load bearing ↓ N — This Asset will not be inspected

Load bearing ↓ N — This Asset will not be inspected Conduct non visual inspection

2 Type of Inspection

The type of inspection to be conducted will be determined by the table below.

A partner project is underway to review alternate methods of inspection. Tap testing of tiles is thought to be feasible for the Shells. Other non-destructive methods may also provide suitable methods of determining an asset's condition.

As the application of the strategy develops over time, it is expected that other forms of non-intrusive testing will be developed to help us better understand the condition of the concrete.

The inspection of the protective system can be quite challenging, as it not always evident if the system is functioning as intended, or its integrity has been breached in some manner. Often, failure is only evident long after the breach has occurred and damage has commenced to the asset it was meant to be protecting. As such, a visual inspection of the protective system is the first method of investigation.

4a

Determine type of inspection →

4b

If Accessible, determine if non visual inspection will be considered

2.6

	Guidelines
Low Tolerance for Changee	Cannot conduct intrusive inspection
Moderate Tolerance for Change	May conduct intrusive inspection
High Tolerance for Change	Can conduct intrusive inspection

Refer to Sydney Opera House Maintenance Manural by Arup revised in accordance with current best practice for **Suggested Investigation**

Specialist determines method of inspection

Tolerance for Change ranking of the asset will determine the level of intervention the asset can accept.

Typically, it is not desirable to conduct intrusive testing, but if the asset has Exceptional Significance and / or is of a Load bearing nature, a certain level of intrusive inspection may be necessary.

At all times, when proposing intrusive testing, a Specialist should be consulted to determine if the testing is warranted.

3 Protective System Inspection

The inspection of the protective system can be quite challenging, as it not always evident if the system is functioning as intended, or its integrity has been breached in some manner. Often, failure is only evident long after the breach has occurred and damage has commenced to the asset it was meant to be protecting. As such, a visual inspection of the protective system is the first method of investigation.

5a **Determine type of inspection for protective system** → 5b **Inspect protective system** → 5c **Determine condition of protective system**

2.6

	Guidelines
Low Tolerance for Changee	Cannot conduct intrusive inspection
Moderate Tolerance for Change	May conduct intrusive inspection
High Tolerance for Change	Can conduct intrusive inspection

Refer to Sydney Opera House Maintenance Manural by Arup revised in accordance with current best practice for **Suggested Investigation**

Specialist determines method of inspection

The Protective system in most cases is the surface visible and exposed to the environment. As such, it can easily be viewed. The types of faults may be many and varied but typically the inspector is looking for:

- cracks in membranes
- surface separation
- surface ballooning
- water ingress

A Specialist in Protective systems is normally engaged to assist with the initial setup of the strategy to discuss what Protective systems are in place and how best to inspect and maintain these.

4 Asset Inspection

At this point, the asset has been assigned an identification tag and determination has been made on the:

- Properties of the asset
- Properties of the Protective system if it exists
- Accessibility to the surfaces of the asset
- Importance of the asset

The process has also determined whether it is feasible and warranted to:

- inspect the asset
- inspect the protective system of the asset

For assets that are identified as requiring inspection, type of inspection is determined for:

- inspecting the protective system
- inspecting the asset.

The assets are inspected with the inspection methods deemed appropriate, typically looking for faults that are identified in the list adjacent.

Variances to this list will evolve as technology will allow the invisible to become visible.

- Penetrating style technology may provide insight into cover thickness, condition of steel or stressing cables embedded in the concrete;
- Chemical analysis of bore samples will enable sulphides and other corrosive substances to be studied as to their depth of penetration and likely effect on the reinforcing system;
- Tap testing may provide insight into the drummy condition of the protective system (delamination) or deep cracking under the surface of the asset.

All these results are recorded and assessed to determine the condition of the asset or system.

The condition of the asset is rated either Good, Fair or Poor as explained at 'Determine the asset condition' later in the Framework.

Asset	Identity fault
For visual inspections	Cracking Chipped edge Deflection Corrosion staining Water staining Staining Corroding fixture Spall Erosion Impact damage Delamination
	Refer to sydney Opera House Maintenance Manualby Arup revised in accordance with current best practice for **possible defects**

5 Asset Re-inspection

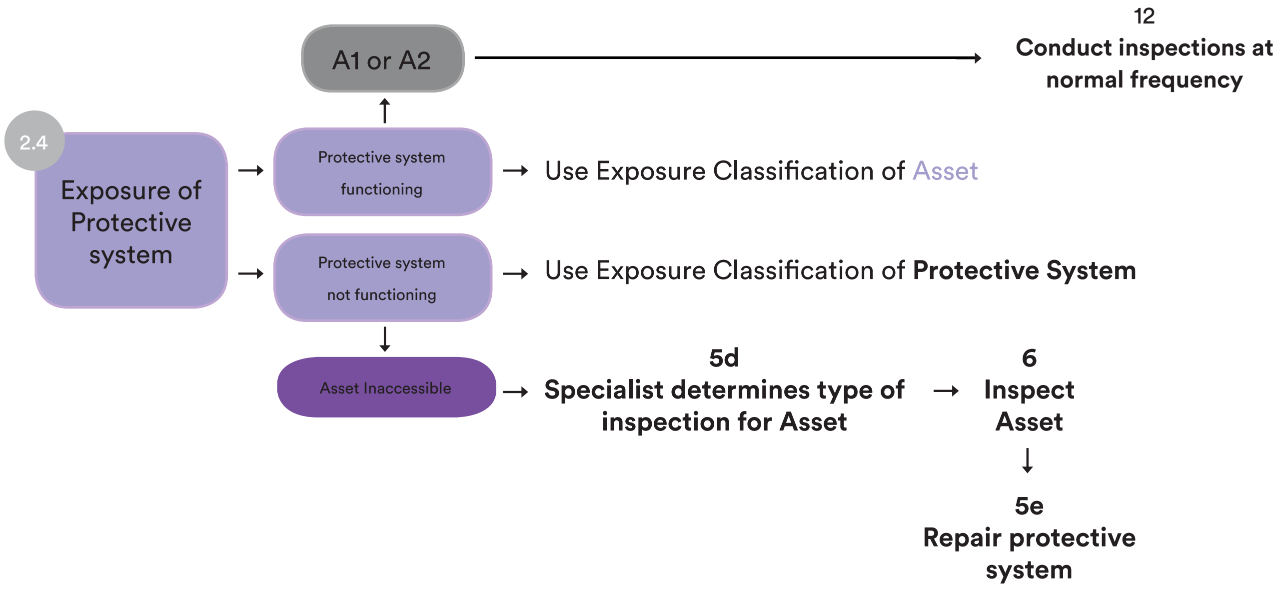
Whilst it is quite simple to begin the process of inspection through the criteria detailed above, the matter of when to re-inspect is not quite as clear.

The re-inspection frequency is determined by Exposure Classification, Level of Significance and Current Condition, which is the main variable in the equation.

It should also be noted that when assessing the asset in regard to Exposure Classification, the Protective system must also be considered if one is present.

If the Protective system is defective, the Exposure Classification for the asset must be downgraded to that of the Protective system and re-inspection calculation performed as if no Protective system existed.

Once the Protective system's integrity is re-established, the Exposure Classification of the asset can then be restored to its original classification if inspections indicate no damage had occurred to the asset during the period of reduced protection.



To determine the re-inspection frequency, the following two tables are used. The first is fairly static and looks at the asset's Level of Significance versus its Exposure Classification.

	Completely protected	**Interior:** Fully enclosed **In contact with ground:** Non-aggressive soils / Above high water level	**Interior:** Repeated wetting / drying	**Exterior:** Above ground **In seawater:** Permanently submerged **In contact with ground:** Below Lowest astronomical tide	**In seawater:** Spray zone	**In seawater:** Tidal / splash zone
	A1	A2	B1	B2	C1	C2
Exceptional significance						
High significance						
Moderate significance						
Low significance						

The second takes this ranking and compares to the asset's current condition to determine the re-inspection frequency. These are currently draft frequencies and will be refined as the process of inspection and condition audit matures.

Good	10 Years	8 Years	6 Years	4 Years	2 Years
Fair	5 Years	4 Years	3 Years	2 Years	Annual
Poor	2 Years	1.5 Years	Annual	9 Monthly	6 monthly

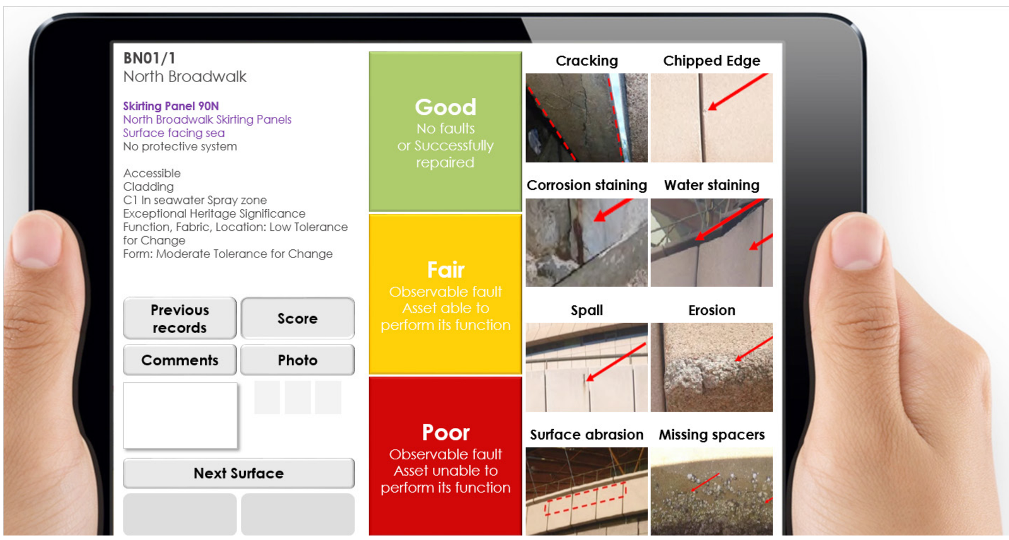
6 Determine the Asset condition

The Inspector will have access to a Conditioning Auditing tool for visual assessment of the asset which will also allow them access to all previous records for the asset they are about to score.

The Inspector will utilise the pictorial guidance of types of faults and determine the level of these faults by assigning a rating of Good, Fair or Poor.

For inaccessible assets, the same conditioning ranking would be used and records stored against the respective asset.

7a **Determine condition of Asset** 7.1 **Good** 7.2 **Fair** 7.3 **Poor**	GOOD	**No observable faults** Includes **successfully repaired** assets
	FAIR	**Observable fault** Asset is **able to perform its function at this time** but is in need of **minor repair**
	POOR	**Observable fault** Asset will be **unable to perform its function** if remedial action is not taken Asset is in need of **major repair** or **replacement**



CONCRETE ACTIONS MATRIX

Develop action matrix

Background

The last phase of the Concrete Conservation Strategy is to determine what actions need to be taken.

At this point, all assets have been:

- Identified
- Classified
- Current Condition Status established; and
- Inspection frequency determined.

The next component of the strategy is to determine what actions need to be undertaken to keep the concrete assets in Good condition.

Principles

Whilst the overarching Principles of the Conservation Management Plan are to be observed for all matters relating to the Concrete Conservation Strategy, this section will also need to consider how each asset is associated with adjoining assets and how these form into systems.

All assets that make up a system are:

- of a similar size and construction
- exposed to similar environmental conditions
- of the same Exposure Classification.

Methodology

Using the information established for the individual assets, the next step is to determine whether to repair or replace the assets. To do this, the assets must first be grouped into Systems.

1 Determine the System

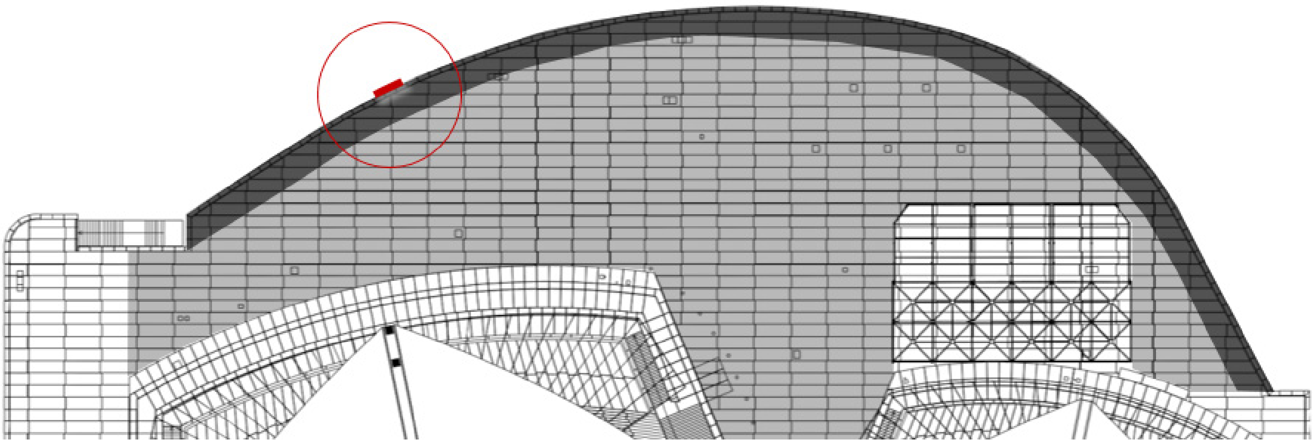
An assessment would be made of all concrete assets, examining their Identification tag and Properties to look for like assets and then comparing this to their geographical location.

The example below looks at a Northern Boardwalk skirting panel and examines all panels of similar tags and properties to determine if there are other assets that are similar.

In this case, it is established that there are many skirting panels with similar tags and properties that are installed along the east, north and west face of the Opera House Broadwalk. The only variance with these panels is the geographical location. It was determined that each face (North, East and West) is exposed to different conditions and wave actions from the surrounding harbour.

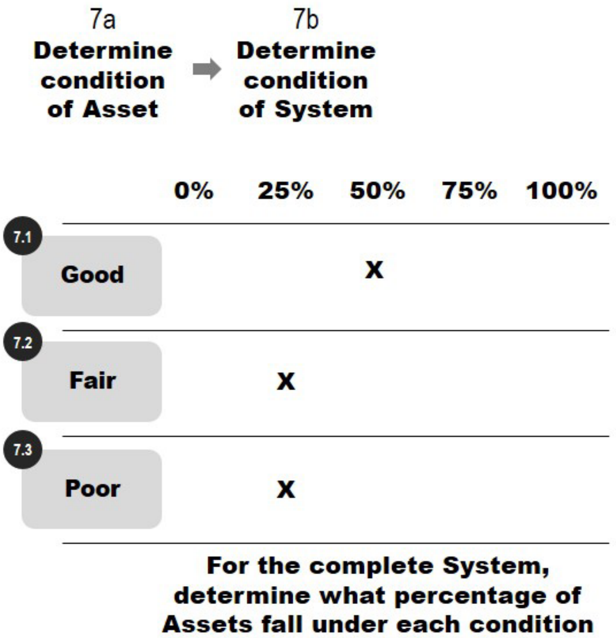
In this example, it was determined that the skirting panels would be grouped into 3 systems, as it was observed that they were degrading at different rates dependent on the 3 geographic locations.

Often, the first condition assessment will provide valuable insight into the possible grouping of assets, as the environment to which they are exposed will have different effects on their performance.



2 Determine Condition of the System

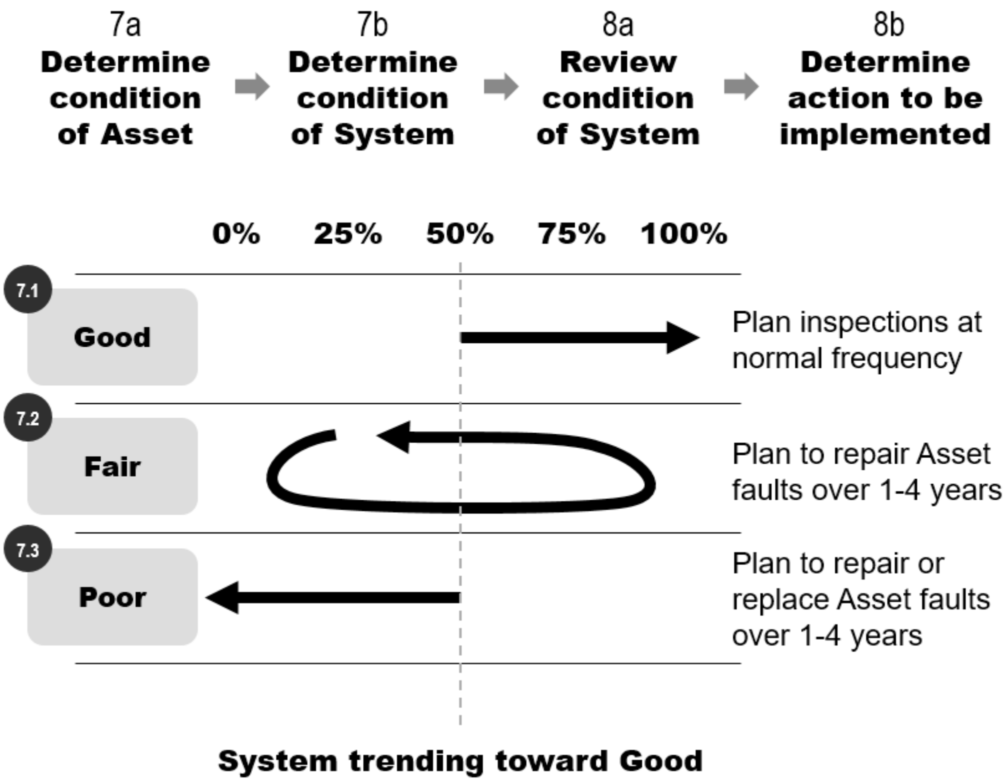
To establish the condition of a system, individual assets will have been inspected to determine each asset's condition. These conditions are then compared across all assets to determine the percentage of Good, Fair and Poor assessments.



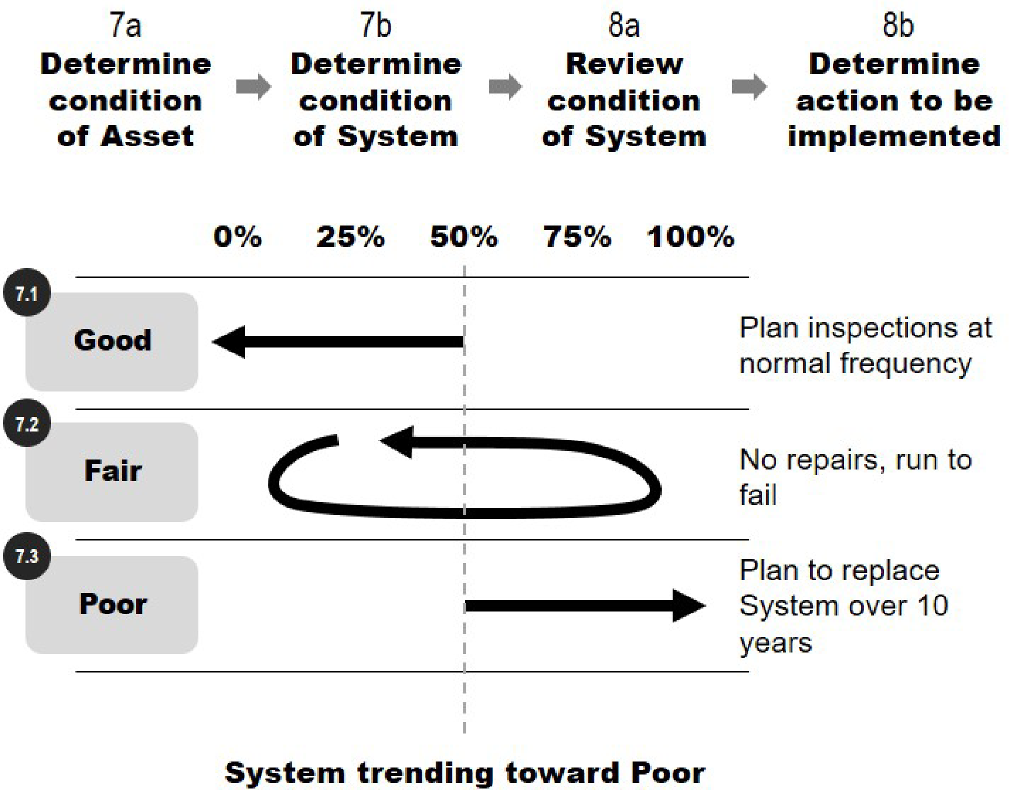
These assessments are then reviewed as per the above table to determine the overall conditioning of the System. Whilst this does not provide a single score, it does give a general picture of how the system is performing by the spread of scores. This spread of scores then provides an indication of the next action to be taken.

3 Asset and System Actions

The intent of the system approach is to assist in planning what action to take for individual assets: repair or run to failure. The tables below provide the general approach. If the majority of the assets in a system are trending towards Good, then the strategy is to continue to repair the faults in the assets and / or replace individual assets in a system to maintain the general condition of the System.



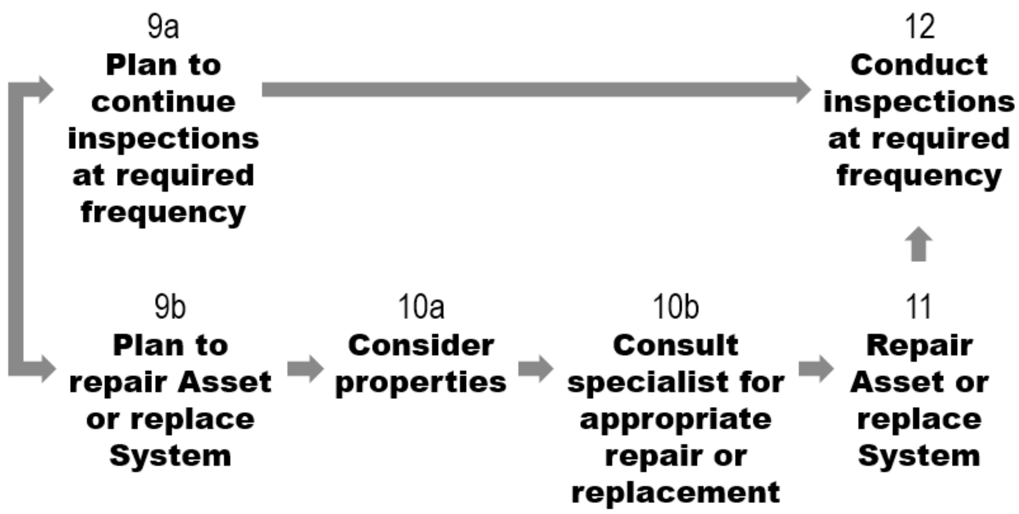
If the majority of the assets in a system are trending towards Poor, the strategy works toward planning and budgeting to replace the entire system and minimising the number repairs during the period to just those assets that keep the System safe and secure.



Overall, the System approach allows a more strategic approach to be adopted to the conservation of concrete assets.

4 Ongoing Asset and System Actions

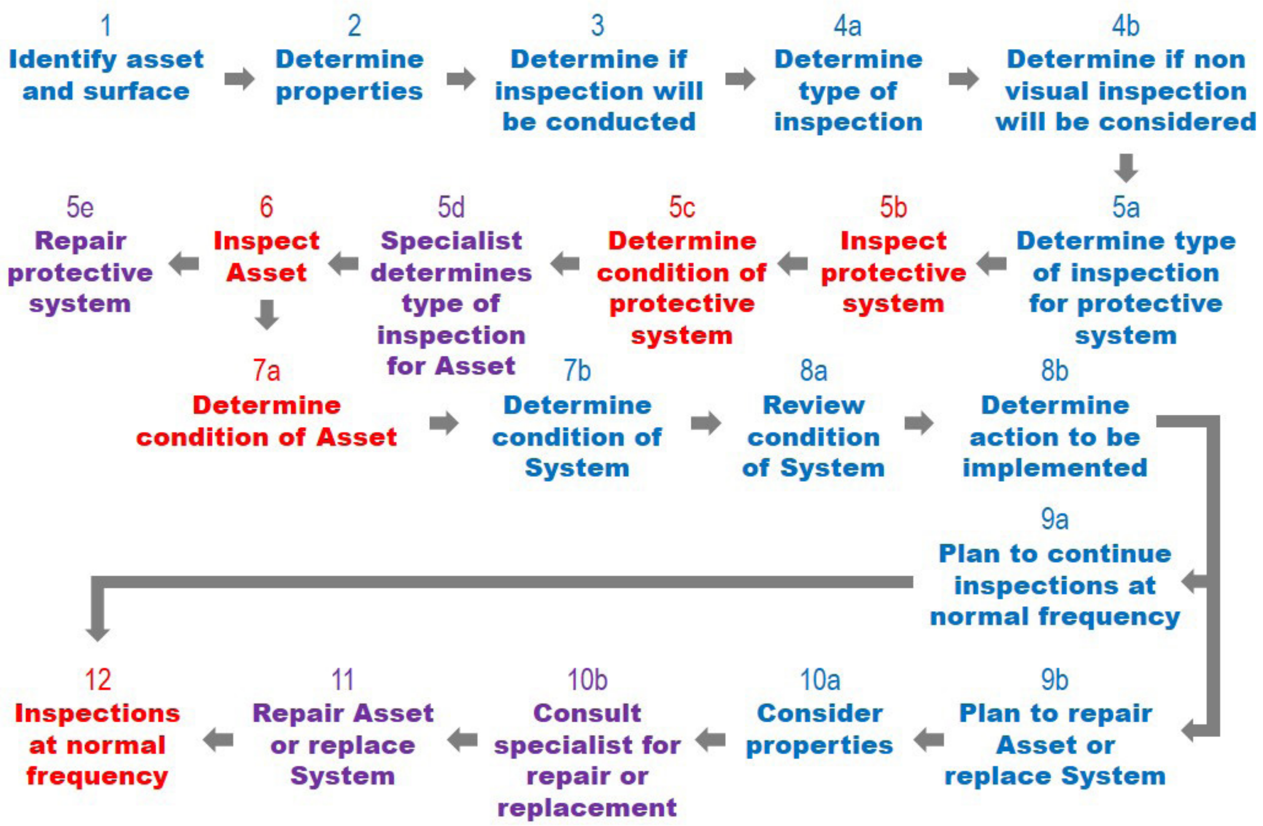
The Concrete Conservation Framework then indicates that the owner / user continues the process of inspection, assessment, planning and repairs in a cycle as defined below.

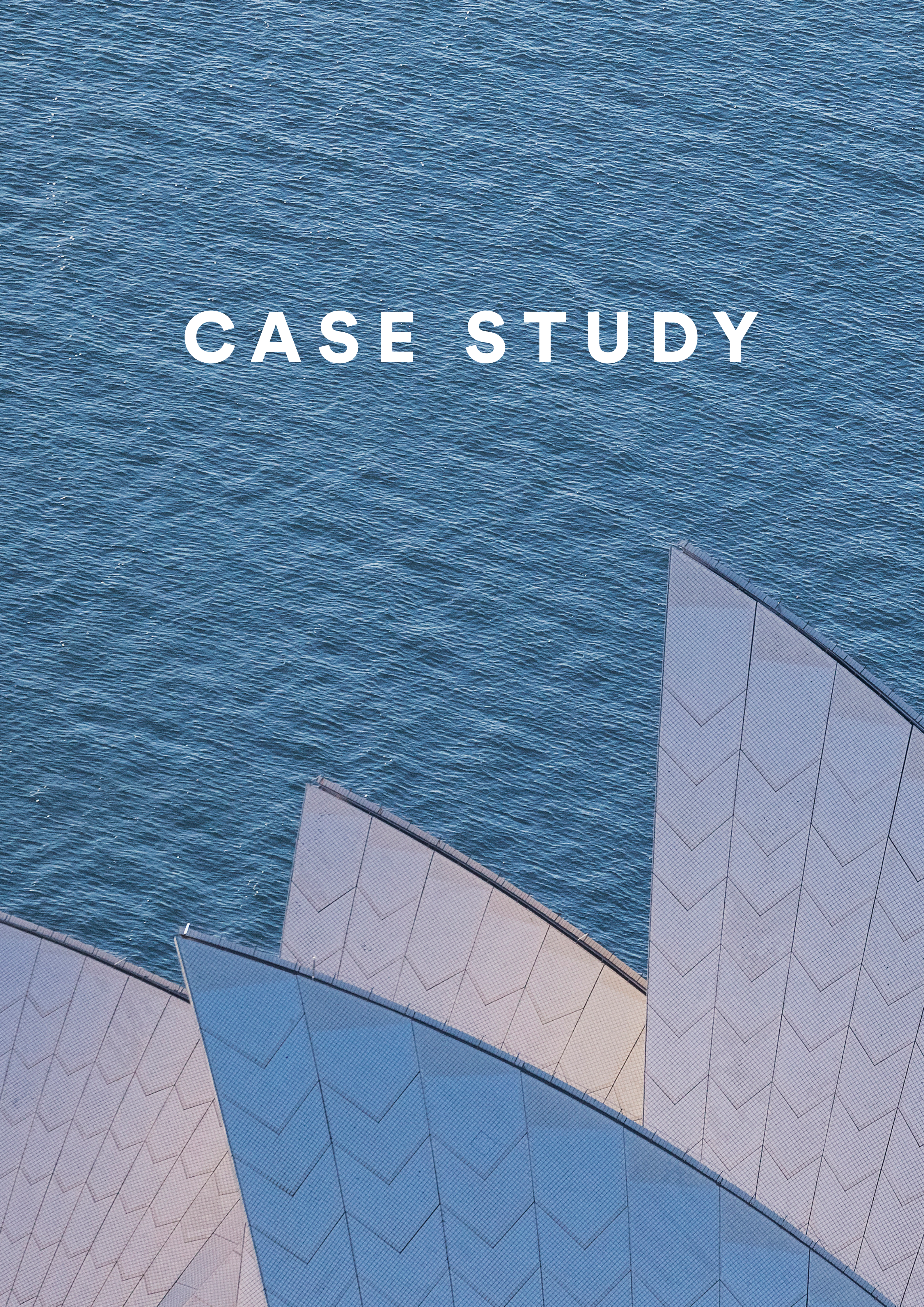


5 Conservation Cycle & Responsibilities

The Concrete Conservation Framework identifies 3 types of participants in the process. The entire process could be performed by a specialist but it is felt that the following is a reasonable approach to resourcing and skill level.

- A Maintenance Professional or Building Strategy team member performs much of the initial setup and ongoing decisions in relation to the strategic direction of the Concrete Conservation Framework. These are denoted as the **BLUE** tasks.
- An Inspector or general Maintenance Technician can conduct the visual inspections utilising the condition audit tool. These tasks are the **RED** tasks.
- A Concrete specialist (Structural Engineer or similar) would provide the engineering or specialist knowledge. These tasks are the **PURPLE** tasks.

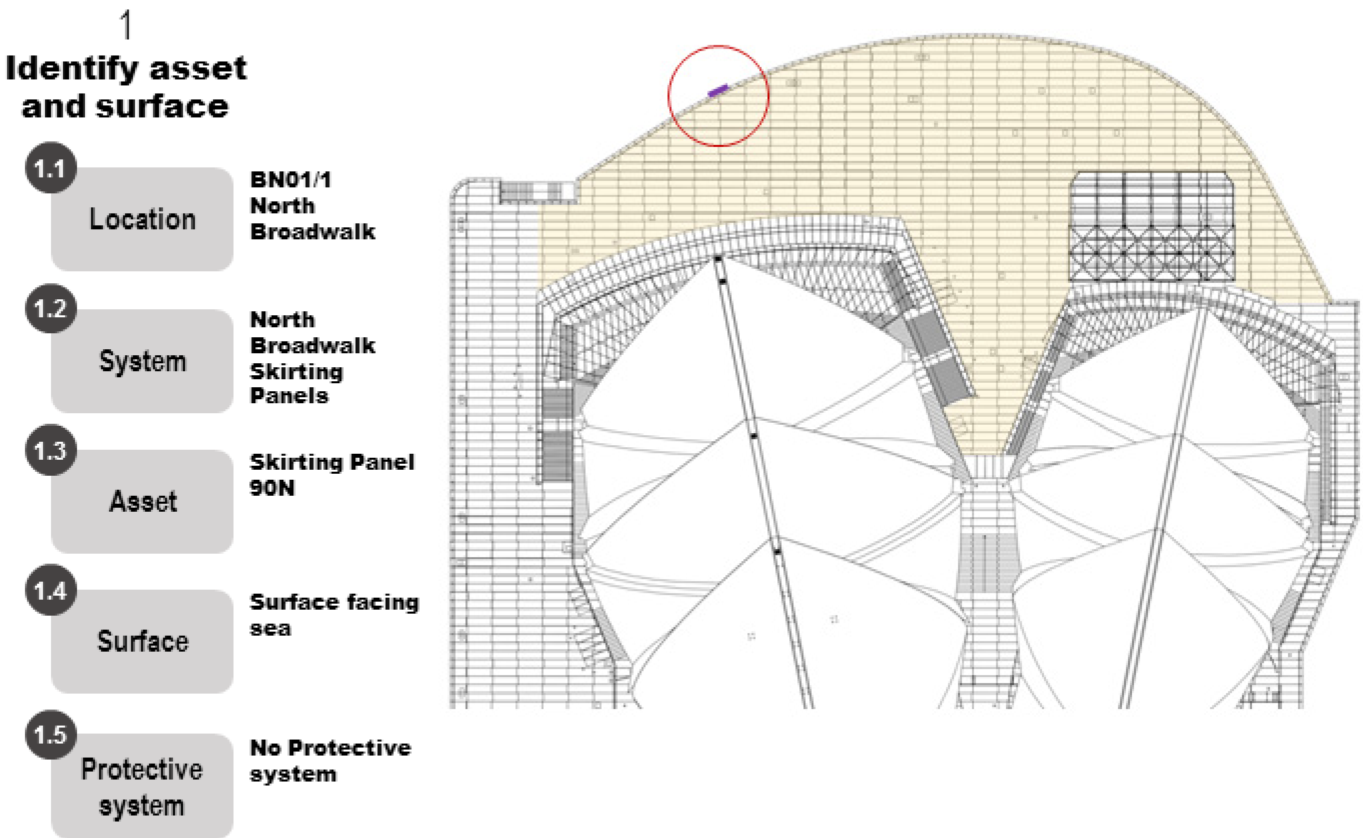



CASE STUDY

To demonstrate the decision making process of the Concrete Conservation Framework, a case study of the harbour facing surface of one of the Northern Broadwalk skirting panels was conducted.

1. Identification of asset and surface

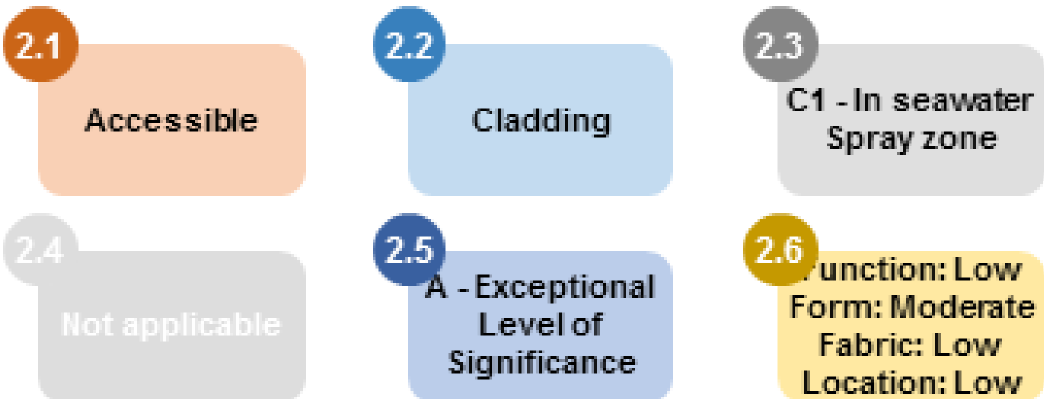
The asset and surface were identified and located. The skirting panel is allocated to room number BN01/1 in the Sydney Opera House rooms database. The asset 90N has no protective system.



2. Define properties

The properties of the asset and surface were determined by assessing its physical and structural properties and by referencing the AS 3600 Australian Standard for Concrete Structures and the Sydney Opera House Conservation Management Plan.

Because it had been determined that the asset has no protective system, the property pertaining to exposure of protective system (2.4) is not applicable.



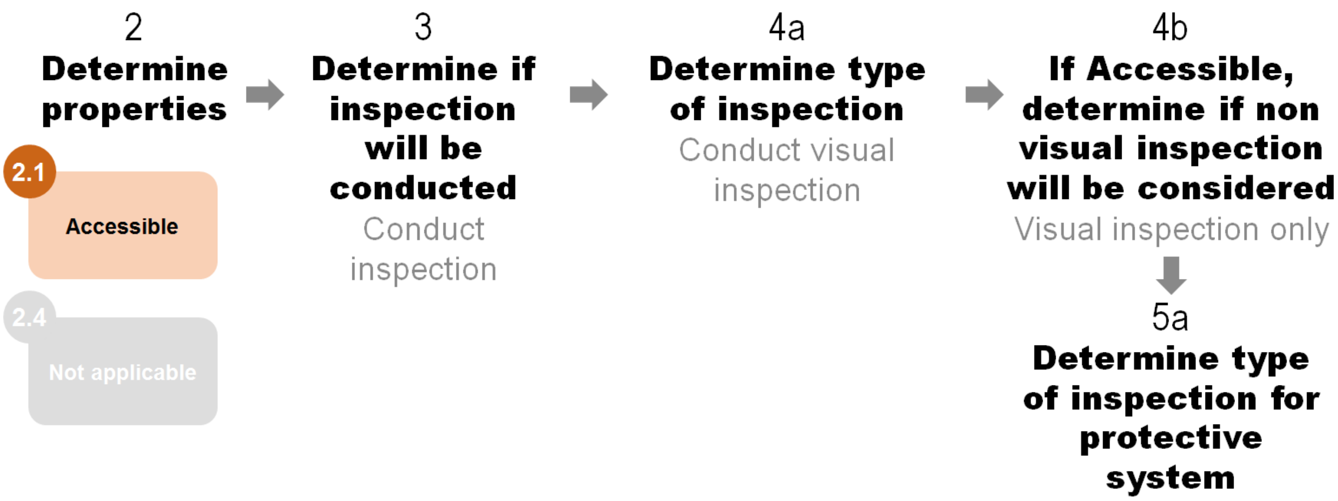
3. Define type of inspection for asset and protective system

The type of inspection to be conducted on skirting panel 90N is determined by its accessibility, structural role and level of significance.

Because the skirting panel is accessible, a visual inspection shall be conducted.

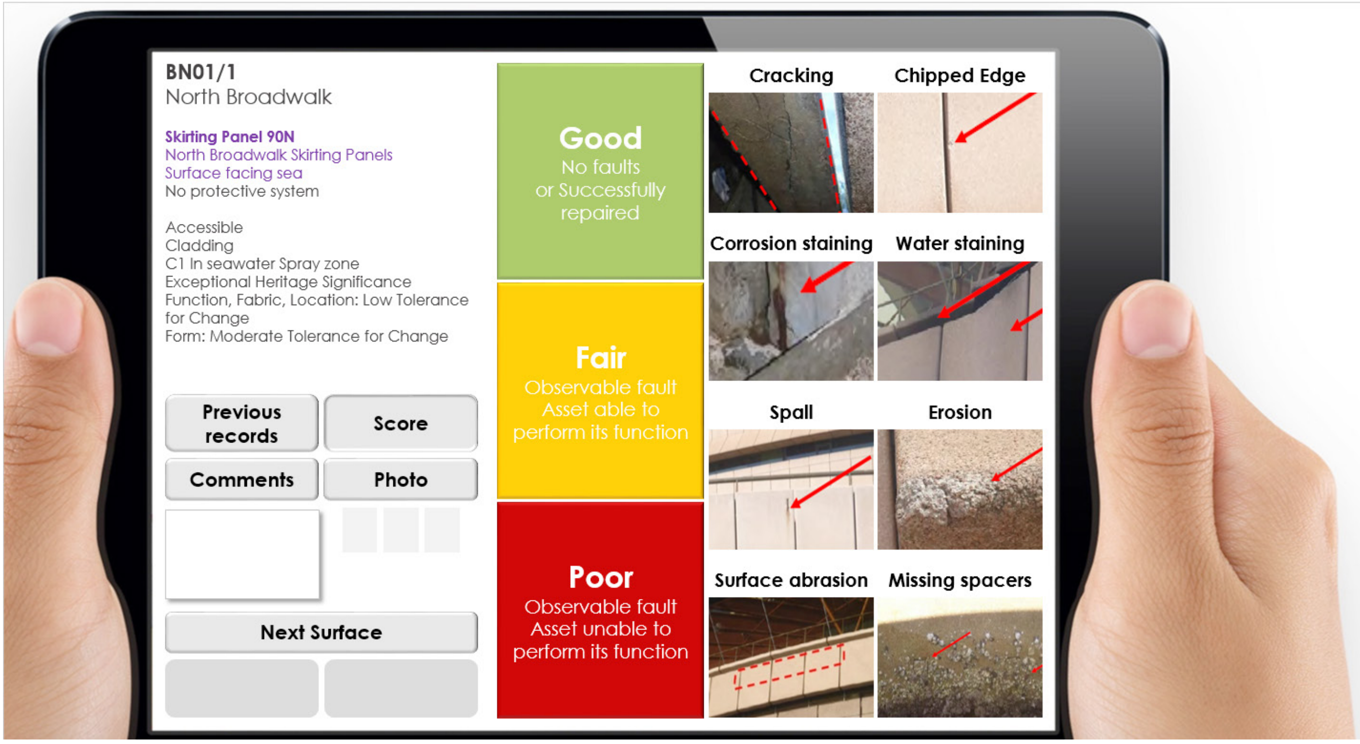
Further inspection is conducted on assets that have both a load bearing structural role and an exceptional level of significance. While the skirting panel is of exceptional significance, its structural role is only cladding. Therefore, further inspection shall not be conducted.

Because the asset does not have a protective system, no inspection shall be conducted for a protective system.



4. Conduct inspection of asset and determine condition

The asset skirting panel 90N is visually inspected by a trained Sydney Opera House inspector. The inspector takes a mobile device during the inspection. It contains photographic references that indicate types and severities of faults likely to be encountered for each asset and surface type.

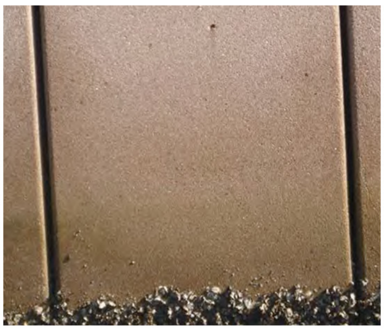


The inspector determines that skirting panel 90N shows signs of spall.

Reference photos are comparable to a severe case of spall, therefore it is determined that the asset is in poor condition.

6b
Conduct inspection of Asset
Spall discovered

7a
Determine condition of Asset
Poor



5. Determine condition of system

The results of the inspection of skirting panel 90N are collated with the other skirting panels that comprise the North Broadwalk Skirting Panels system.

The collated results show the condition of the system:

5% of skirting panels are in good condition

25% of skirting panels are in fair condition

70% of skirting panels are in poor condition

7b

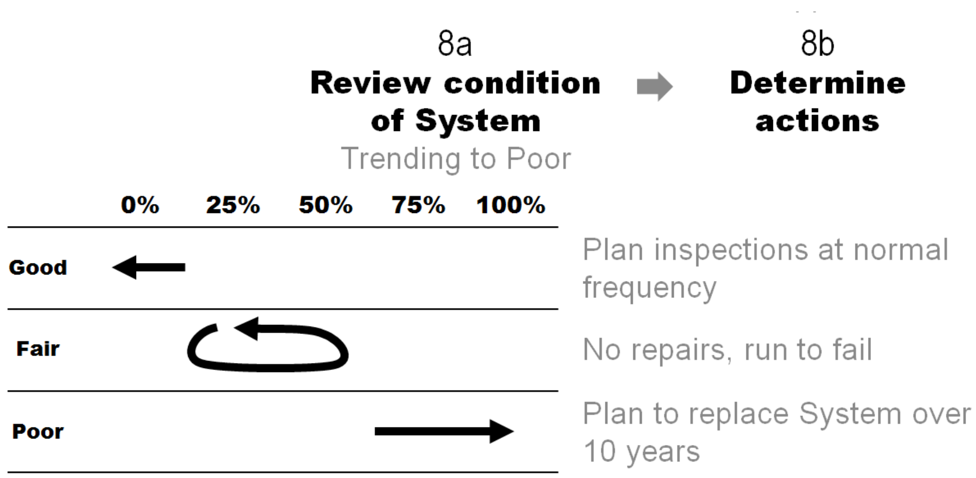
Determine condition of System

	0%	25%	50%	75%	100%
Good	X				
Fair		X			
Poor				X	

6. Review condition of system and determine actions

In this hypothetical example, it is determined that the system is trending to poor overall condition. One possible action to consider might be to replace the entire North Broadwalk Skirting Panels system over the next 10 years.

Actions against each skirting panel in the system work toward maintaining these individual assets until the planned replacement of the system is achieved. The assets will be kept in a safe condition until their replacement, essentially run to fail. Actions may still include regular inspections.



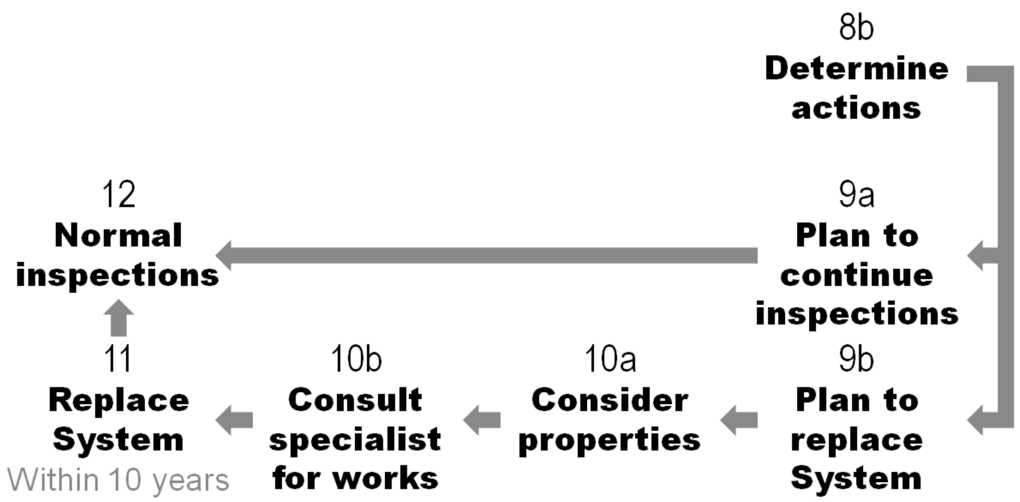
7. Next steps for system maintenance

In this hypothetical example, it has been determined that the North Broadwalk Skirting Panels system will be replaced in the next 10 years. Planning in terms of design, finance, logistics, would then commence.

The properties of the assets are considered in order to determine the most pertinent specialist(s) to consult for the replacement project.

The system is replaced as planned, and normal visual inspections are recommenced.

During this time, normal inspections will continue to ensure the system remains in an acceptable condition until its replacement.



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'Sydney Opera House
Concrete Conservation Project
Final Report Summary', August 2018
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