Bronze Componentry Project

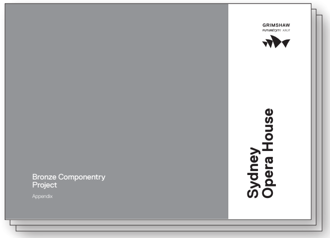
Volume 1 — Design Investigation

GRIMSHAW

PRISM Façades | ARUP

Sydney Opera House

Volume 1 in context



Bronze Componentry Project Reports:
Volume 1: Design Investigation
Volume 2: Design Manual
Volume 3: Appendices

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Volume 1

Design Investigation

Introduction
The Design Investigation in context

As it grows into the 21st century, the Sydney Opera House Precinct is meeting new opportunities and facing new challenges as Australia's pre-eminent Performing Arts venue. Addressing these challenges requires a careful consideration of existing design ideas and solutions in light of these changing conditions and ambition. As with any project centred on a heritage asset, there are invaluable guidelines to refocus Design Principles, enduring aspirations, and legacy that must be interwoven with the current brief and stakeholder input. This report synthesises and evaluates the breadth of past and current design thinking and practice as it pertains to the Opera House's bronze componentry.

The Bronze Componentry Project couples industrial design with engineering to create a new suite of multi-functional handrails and barriers for both the interior and exterior of the Opera House. The project aims to improve venue accessibility and safety for all visitors, including those with disability, while also enhancing the visitors' tactile experience of the precinct in a manner that is consistent with the heritage values of the Sydney Opera House. The Design Investigation marks the initial study phase of this work.

Grimshaw has taken the existing handrail placement plan originally developed by the Government Architects Office in 2014 and used this as a foundation for an expanded handrail and barrier naming strategy. While the previous study primarily proposed a replacement strategy, the current Bronze Componentry Project focuses on assigning crowd loading categories to each handrail and barrier type given its specific location.

Bronze componentry is a highly significant heritage and tactile element of the Opera House. Its upgrading, design and care requires great sensitivity to current and future needs and conditions. In the past, where new bronze componentry has been added, these efforts have generally been undertaken in a considered but limited scope.

The project presents an opportunity to address the Opera House's bronze elements with a holistic approach, taking into account the needs and conditions across the site. The project aims to capture the full quantum of bronze componentry at the Opera House, ensuring that bronze future works can be undertaken in a cohesive manner across a range of current and future upgrading projects, and in the course of normal maintenance, helping to ensure that lead times, manufacturing processes and procurement costs can be made as efficient as possible.

Grimshaw's approach for the Volume 1 Design Investigation combines document research with physical investigation, synthesising past understandings with new findings related to bronze componentry. This research sets out the breadth and depth of past and current design thinking. It underpins and serves as the framework for the Volume 2 - Design Manual, which carries forward the learnings from Volume 1 and realises them into innovative and responsive design solutions that respect the sensitive heritage environment of the Opera House while looking to meet the requirements of its future.

Introduction
Design Investigation background, approach and structure

This report builds on previous design and investigation studies, most notably the 2014 'Handrail and Balustrade Masterplan' prepared by the Government Architects Office. This masterplan identified over 40 types of barrier and handrail systems in use at the Opera House, fabricated in four main profile types. These systems ranged across different materials and assembly configurations. The task, then, was to undertake a review of past studies, complete new investigations, and build on existing knowledge and understandings of the Opera House's bronze componentry in order to inform a new and more responsive design approach.

Existing Document Appraisal
As a starting point, the Grimshaw team undertook a review of the canon of major ideas, designs and research amassed at the Opera House over the past 27 years. Coalescing the content of 14 studies providing invaluable insight into their relevance for the future of the Opera House, both for the project team and as a further reference document for the Building Renewal Team's future works. Critically, their analysis provides a framework for the initial design investigations.

Opera House Storage Facility Audit
Grimshaw undertook a physical audit of the Opera House's storage facilities in Leichhardt and St Peters which houses building fabric and componentry. The project team inspected used and unused sections of original bronze extrusions, and unused barrier sections from the Western Concourse (2008). Valuable new findings included a physical document of past assemblies and patina. Research provided insights into the fabrication process, and contained marks from the makers hand, some 45 years prior.

Studies
The project team carried out a number of key research studies to develop a better understanding of the technical and conceptual underpinnings of the bronze componentry. These studies document key points of research, site measurement, photography, drawing and detailing and physical modelling conducted by Grimshaw and our nominated consultants. They illustrate and explore the unique and varied stairs and building geometries found on the exterior podium and interior foyers, as well as key material and geometric properties of the barriers and handrails.

Design Criteria & Engineering
The project team then synthesised research established through the document appraisal, storage facility audit, and study series, in order to establish a set of design criteria and engineering specifications specific to the design of the new barriers and handrails. Notably, these criteria establish the existing post locations and spacing to set out the new design and the use of a dominant top rail.

These design criteria and specifications ensure that any new design proposal will meet the needs and conditions of the site, fulfil engineering requirements, mitigate any constraints, and rise to the standards of the highest principles of the Opera House's design legacy.

Existing Conditions
Site conditions and design criteria and engineering specifications were taken together to develop a range of handrail and barrier assemblies that could accommodate the existing exterior and interior conditions of the Opera House. These assemblies, using existing mounting points, test set-out and infill options while also incorporating current code requirements. They enabled the project team and stakeholders an opportunity to review and contrast new assembly options against the original installation.

Through consultation with the Opera House's Eminent Architects Panel (EAP), a refinement of assemblies produced a preferred option to satisfy each condition - a vertical rod infill on the exterior and an internally glazed infill on the interior. These assemblies and other considered options are presented for comparison in a table format.

Materials & Process
The final section of this report outlines key information relating to the materiality and manufacturing processes required for future barrier and handrail works. This content addresses requirements and recommendations related to the selection and use of bronze alloy. Additionally, bronze manufacturing processes - including extrusion - are considered and compared. When evaluated against conventional extrusion, alternative processes proved to be too expensive or could not achieve the complex profiles required to extend the existing facade nosing and sill profiles.

Finally, a preferred extrusion supplier is identified, following a global search of suitable production mills across Europe, Asia, South Pacific, Americas and South Africa.

Chapter 1

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Existing Document Appraisal

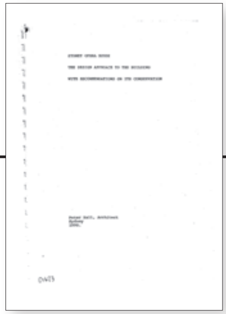
Existing Document Appraisal
Context, auditing, research and engagement

As a starting point for the Design Investigation, the Grimshaw project team undertook a review of the canon of major ideas, designs and research amassed at the Opera House over the past 27 years. Specifically, the team undertook a review key documents identified for their particular significance to bronze componentry across the Opera House and Bennelong Point Precinct. Their contents spanned technical and conceptual information related to design criteria and principles, alloys and materiality, profiles, assemblies and fixings, lighting design and history, relevant planned and ongoing works, and maintenance and conservation.

Coalescing the content and nature of these works provides invaluable insight into their relevance for the future of the Opera House, both for the project team and as a further reference document for the Building Renewal Team's future works. Their analysis ensures that expertise and understandings from past design thinking, evaluation and execution are considered and carried forward where appropriate.

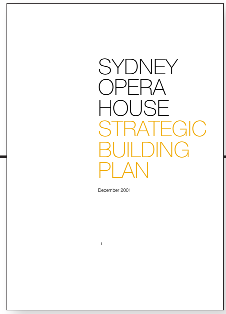
In total, the Opera House team provided Grimshaw with 14 documents for review. The diagram (overleaf) depicts a chronology of these documents - a 'from where' and 'to where' - leading to Volumes 1 & 2 of the Bronze Componentry Project. An appraisal of each document is catalogued on the following pages. Their analysis provides a framework for the initial design investigation.

01.



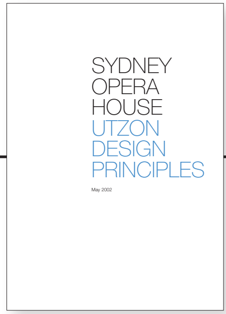
SOH The Design Approach to the Building with Recommendations on its Conservation, Hall 1990

02.



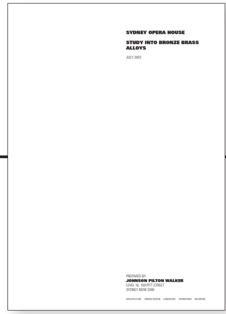
SOH Strategic Building Plan, SOHT 2001

03.



Utzon Design Principles, SOHT 2002

04.

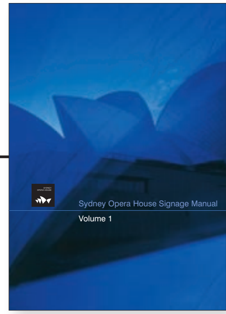


SOH Study into Bronze Brass Alloys, JPW, 2003

05.

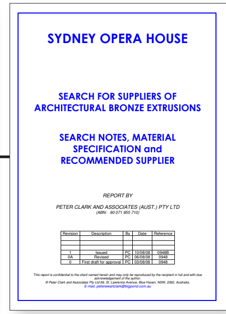
Report on the Maintenance Of Bronze Components, Sydney Opera House, Issue C, Lucas Stuart 2005

06.



SOH Signage Manual Vol 1 & 2, Emery Frost 2006

07.



SOH Search for Suppliers of Architectural Bronze Extrusions, Clark & Hyder Consulting, 2008

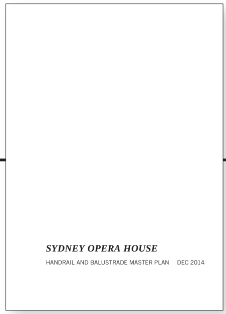
08.

SOH Forecourt Parapet Panel & Handrail Works (Stage 1) - Technical Specification, SOHT & Hyder Consulting, 2008

09.

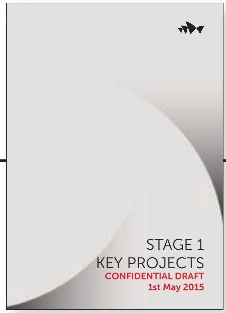
SOH Balustrade and Handrail Design Stage 1 Working Group Report, SOH & Utzon & JPW, 2009

10.



SOH Handrail and Balustrade Masterplan, NSW Government Architects, 2014

11.

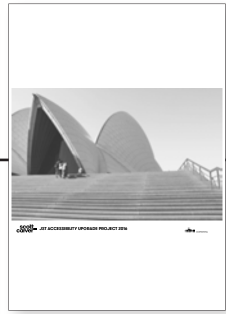


SOH Building Renewal, T. Sloan & L. Smith 2015

12.

SOH Accessibility Masterplan Issue C1, Scott Carver Architecture & Design 2015

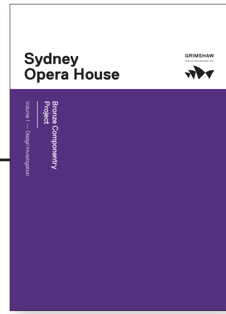
13.



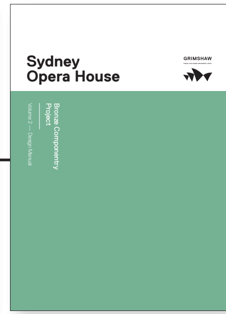
JST Accessibility Upgrade Project , Scott Carver Architecture & Design, 2016

14.

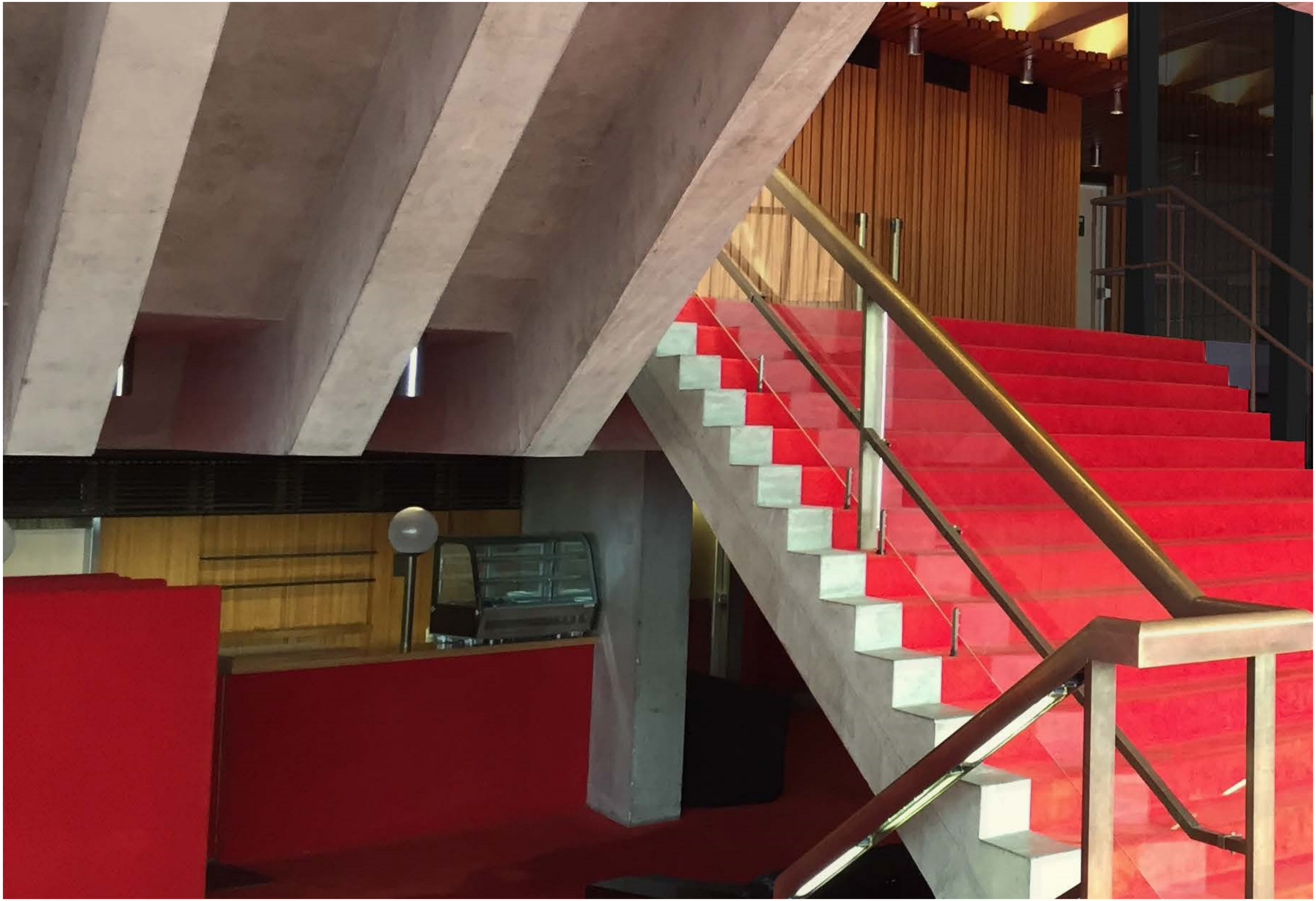
Conservation Management Plan Ed.4, Alan Croker 2017



SOH Volume 1 Bronze Componentry, Grimshaw, 2017



SOH Volume 2 Bronze Componentry, Grimshaw, 2017



Document 01

Sydney Opera House, The Design Approach to the Building with Recommendations on its Conservation, Peter Hall, 1990

Peter Hall's documentation of the work he conducted throughout the building of the Opera House provides a valuable insight into the process of delivery and design decision making. The document catalogues a number of correspondents and includes a transcript of a lecture given by Arup's Jack Zunz to the Royal College of Art in 1987, itself an interesting and thorough recollection of the projects development.

The document includes commentary on the later works associated with the Forecourt ground surface and construction of the Lower Concourse and associated amenities in the late 1980s. There is a comprehensive finishes schedule provided for the original rooms at the Opera House and extensive information on the paving, cladding and glazing. The document covers the design and development of the Concert Hall in some detail, with particular reference to the acoustics, finishes and even seat numbers and design.

Dependencies / associated materials:
This document should be considered with respect to:

- Strategic Building Plan (2001);
- Utzon Design Principles (2002);
- Conservation Management Plan (2017).

Specifics relating to Bronze Componentry:
This document is an excellent record of the Opera House in the early 1990s and is a useful source of information. It is a historical document and should be used, where appropriate, to provide an insight into the story of delivery and construction of Opera House. This is not a guideline document and needn't inform future decisions or direction but it does provide an informative insight into the design and construction of the Opera House by one of its key creators. The document does not need to be updated or modified, but should be preserved as archive and reference material.

Document 02

Sydney Opera House Strategic Building Plan, Sydney Opera House Trust, December 2001

The Strategic Building Plan (SBP) was produced in 2001 to "progressively improve the building, eliminate functional deficiencies, improve the interiors of the building and ensure the long-term viability of the Sydney Opera House." The Strategic Building Plan set the foundation for future building renewal at the Opera House.

The SBP seeks to address the immediate and long term aesthetic and functional needs of the Opera House. The document presents an appropriate and necessary programme, enabling future viability for the Opera House and the vision it embodies. The SBP is envisaged as a series of projects that can be implemented over time, enabling a greater level of resolution of detail, and providing a basis for funding and implementation. The document highlights the limitations associated with the Opera House, and identifies the shift in user requirements during construction (without alteration to the building envelope) as a principal cause of deteriorating functionality of performance and back of house spaces.

The document presents a strategy for the reclamation of the central corridor through the careful relocation of plant facilities and functions and performance driven requirements. There is a provision within the strategy for a new lift and escalator within the forecourt (nearby the Bennelong Restaurant) which has been built. There is a general provision for the installation of a number of lifts identified in Utzon's original plans which would enable the accessibility of the Concert Hall and Joan Sutherland Theatre to be better realised. The SBP has identified a need for flexibility in the back of house and performance spaces - this is largely due to the evolving nature of the project and the fact that the user requirements for the Opera House changed from the original brief. It has become physically difficult to rectify some of these deficiencies.

The proposed solution is to increase the space below the Forecourt not only to manage increased loading, but to provide greater Back of House space and performance rooms.

The strategy itemises the following essential projects / areas for review:
Joan Sutherland Theatre;
Concert Hall;
Drama Theatre and Playhouse;
Forecourt;
Utzon Room;
Opera and Concert Foyers;
Western Foyers;
External Spaces;
Office and rehearsal Rooms;
Dressing Rooms;
Storage;
Central Passage;
Vehicle Concourse.

The strategy lists the following key Concept Planning Projects, their status and opportunity for enhancement:
The Overall Site;
The Podium Level;
The Box Office Level;
The Ground Level;
The Lower Ground Level;
The Lowest Basement Level;
The Central Passage.

Specifics relating to Bronze Componentry:
Envisaged as a series of projects that can be implemented over time, enabling a greater level of resolution of detail, and providing a basis for funding and implementation. Provides a broad vision to achieve two objectives: to develop and safeguard the Opera House and its site for the benefit of future generations; identifies the need to redress the practical limitations affecting the functioning of the building as a very busy contemporary performing arts centre and visitor attraction. The SBP sets a clear vision for the "need to improve access to the building for all visitors, including people with disabilities."

Important document with respect to opportunities afforded to the design team for the handrails, barriers and other bronze componentry, highlighting the arrival through the precinct to the venue as being of significance. The SBP noted that some existing handrails and barriers do not meet current public expectations and code compliance in terms of rail profile dimensions, rail height, lighting, and infill material. A well designed and built upgrade would provide a significant improvement to access and safety for all visitors and staff, including those with disabilities.

Document 03

Utzon Design Principles, Sydney Opera House Trust, May 2002

On the 25th anniversary of the Opera House, the Sydney Opera House Trust set out to establish two fundamental objectives:

- To safeguard the Opera House and its site for the benefit of future generations;
- To address the effectiveness of the building function as a contemporary performing arts centre.

In May 2002, Jørn Utzon produced the Utzon Design Principles (UDP) in consultation with Sydney architect Richard Johnson. This overarching guide document articulates the sources of Utzon's inspiration and design vision, together with the principles he saw as underpinning future maintenance and adaptation of the building.

Prepared by Utzon, this document outlines his vision for the building and its setting, as well as comments on the future. It is intended as a permanent reference for the conservation of the building and its setting. It can be used to clarify design intent, to manage proposals for change and influence planning controls for the precinct. The document offers the complete narrative of the architectural intent of Utzon and provides complete and comprehensive principles for the Opera House when it was conceived, designed, and delivered, and for its future. This document is a key resource, and remains entirely relevant and useful. All future works must consider the UDP to ensure consistency with Utzon's original design intent.

Document dependencies / associative material:
The document is generally regarded as a standalone document, however it can be read in conjunction with the following:

- SOH Strategic Building Plan (2001);
- Conservation Management Plan (2017).

The document forms the backbone to all design work associated with the Renewal projects and all design developed or proposed refers back to this document.

Specifics relating to Bronze Componentry:
Design concepts and development of bronze componentry should comply with the Utzon Design Principles in terms of:

- Orientation and Movement: to ensure more fluid, safe and equitable access – the implication being that all opportunities should be taken to minimize obstructive or unnecessary handrails or barriers;
- Additive Architecture: componentry should be produced industrially, geometry and form should have harmony and uniformity.
- Pre-fabrication: machine-made components, modular coordination/standardization, repeated form – supporting a construction system for off-site pre-fabrication and ease of maintenance and replacement when required;
- Structural expression: exposing materials, acquire patina without changing character, weathering, simplicity in numbers of materials – bronze to match the existing would be preferred;
- Light: to flatter human skin and hair, indirect with custom design fittings, concealed handrail lights, minimise reflections / maximise views - implications for concealed lighting and reflectivity of infill material – Utzon was adamantly against the use of glass in the external handrails;
- Process: full size mock-ups as a design and construction tool, models, work in collaboration with manufacturer.

Document 04

Sydney Opera House Study into Bronze Brass Alloys, Johnson Pilton Walker, 2003

The report documents the existing Bronze alloys at the Opera House and investigates alternatives where procurement of the existing specification is difficult. Information was obtained primarily through conversation with various brass bronze workers in the trade with experience on the Opera House.

Document dependencies / associative material:
This document is generally regarded as a standalone document which catalogues the first efforts in the renewal period to systematically address the specification and use of new bronze material within the Opera House.

Specifics relating to Bronze Componentry:
Findings situate bronze as a significant and prominent material within Opera House, identifying handrails, glazing sections, signage hampers, door hardware, and drinking fountains bollards as extruded, cast or clad in bronze. Specifies that new bronze work should be in keeping with the appearance and feel of the existing bronze.

Specifications provided in the document are summarized as follows:

- Extrusions (large jobs, where time permits): specifies C67800 Manganese (lead free) Bronze (not available in sheet form) for consistent appearance with the existing bronze - requires new dies, as original dies no longer exist and reproductions require costly and time consuming retooling.
- Extrusions (small jobs/limited time): use simple stocked sections in C38000 Section Brass or 380 brass flat bars and angles and using a chemical ageing process match existing patina.
- Sheet Bronze: specification not clear, likely Cartridge Brass or Naval Brass (corrosion resistant characteristics with similar chemistry to the Manganese Bronze and having a 60/40 Copper/Zinc ratio and could achieve a similar brown patina.
- Bronze castings: (drinking fountains, service bollard, external lamp posts, etc.) specified as C83600 Leaded Gunmetal Bronze have aged to a slightly greener tinge than the Manganese Bronze extrusions.
- The report suggests that the most significant aspect to consider in specifying new bronze is the patina of age. Artificial ageing – done with care - will be necessary to avoid a patchwork of new and old bronze and brass.

Document 05

Report on the Maintenance Of Bronze Components, Sydney Opera House, Issue C, Lucas Stuart, 2005

This document assesses all the applications of bronze across the Opera House site and makes detailed recommendations for its maintenance and repair, with reference to Utzon's preferences, and notes that there has been no preventative maintenance program for the treatment and care of bronze components since the completion of the Opera House. Components are showing varying degrees of surface build-up and corrosion, causing visual disfigurement and pitting. Auditorium handrails and the interior bronze extrusions exhibit a stable slightly tarnished surface while louvre walls below the shells are the most corroded area of the building. The report recommends cleaning and colouring processes and approaches for antiquing new bronze, and recommends a further condition assessment in ten years time to assess progression of corrosion and effectiveness of treatments recommended.

Document dependencies / associative material:
This document is generally regarded as a standalone document, however it can be read in conjunction with the following:

- Utzon Design Principles (2002);
- Sydney Opera House Study into Bronze Brass Alloys (2003);
- Conservation Management Plan (2017).

Specifics relating to Bronze Componentry:
The document recommends the continued use of Alloy 412 due to its proven durability. The mill finish should be retained on the extruded 'bronze' with some localised site linishing to bring the welded joints to a uniform appearance. Alloy 412 has performed significantly better than more recent standard section brass or even other unleaded manganese bronzes (Alloy 678) that were used in the 1988 Lower Concourse and at Circular Quay Station in 1999. The report recommends that the Opera House procure and keep up a stockpile of 9" and 11" ingots of Lead Free Manganese Bronze (Alloy 412) for use in repair and new bronze work.

Regarding the colouring of new bronze, in order to ensure compatibility, new bronze should have a light artificial colour applied to allow the metal to fully develop the full reddish brown tarnish over time.

Sodium bicarbonate hand washing is recommended for trialling and monitoring. $NaHCO_3$ solubility can be improved by accelerating the cleaning solution with Carbon Dioxide (CO_2). Machine buffing procedure: patina can be burnished back in order to remove harmful corrosive salts.

Regular waxing: not previously specified, but regular application is specified to ensure that the bronze retains its longevity, and remains aesthetically acceptable.

Cleaning and colouring processes and approaches are specified for: Bronze Louvre Walls; Interior Bronze Louvre Grilles; Bronze Louvre Grilles; Bronze Tilt-a-Way Doors; Bronze Floor Grates; Lamp Posts; Drinking Fountain; Barriers and Bollards; Bronze Handrails; Glass Wall System; Bronze Doors; Transom Signs and Hardware; Signage & Vitrines; Floor Strips; Service Covers.

The authors stipulate that cleaning and treatment (or introduction of new bronze) should be carried out in accordance with Opera House Conservation policies (3rd Ed), which have since been superseded by the CMP 4th Ed. (2017). However, the document notes that a cleaning technique - involving the use of olive oil - has been successfully used on site for a number of years. Additional recommendations regarding materials, manufacturers, significance, treatment and maintenance will need to be revised in light of further assessment due to the passage of time.

Document 06
Signage Manual Vol 1 & 2, Emery Frost, 2006

The document provides the previous comprehensive review undertaken for signage in the Opera House Precinct prior to the Precinct Masterplan Signage Audit (2016). The document was produced as a management tool with respect to all signage within the Opera House site boundary. Volume 1 establishes the heritage significance of the Opera House in relation to signage and the needs and constraints applicable to the Opera House as a contemporary performing arts venue and tourist destination. Volume 1 sets out the key framing and interpretation concerns. Of particular note are:

- Concern for alignment with Utzon's Design Principles; and
- Respect for the distinctive nature, heritage and setting of the Opera House.

The document concludes that there is an excessive proliferation of sign types and forms in the public areas. It notes the development of a signage strategy that derives from a system of mutually supportive graphics and sign elements; the need for respectful and cohesive signage with respect to the Opera House identity; development of a hierarchy of interrelated sign types; reconciliation of key existing signage with the development of new signage that increases the clarity of information presented through reconciliation of numbering systems, communication style, etc.

Volume 2 establishes signage policy and signage recommendations addressing the research and investigation undertaken during the preparation of Volume 1. The document is neither exhaustive nor up-to-date with regard to existing and future signage demands and needs on-site. At this time, the Manual is out-of-date as some recommendations have been implemented, some signs have been replaced outside of recommended guidelines, and other signs may have experienced deterioration or obsolescence in the intervening years.

Dependencies / associated materials:
As the most current published review of signage available on signage to date, the document refers and relies heavily on the following documents and material:

- Strategic Building Plan (2001);
- Utzon Design Principles (2002);
- Conservation Management Plan, Ed. 3 (2004).

The document also informs the following material pertinent to the development of future signage strategies:

- Accessibility Masterplan (2015);
- Precinct Masterplan (2016).

Specifics relating to Bronze Componentry:
The document highlights the dominance of bronze in the existing colour scheme of fittings and fixtures and makes assessments and recommendations on condition and deficiencies of public bronze signage elements across the Precinct. It is noted that the existing bronze-finish signage is not successful as it blends too well with its surroundings and the information content is not visible enough. Also notes City of Sydney and The Rocks' signage use bronze as a signage material. The City of Sydney street furniture, phone enclosures, etc. have a bronze finish and The Rocks wayfinding elements also have a bronze finish. This common material sits well with the use of bronze for external fixtures at Sydney Opera House. The document establishes base metrics for the identification and assessment of existing signage at the Opera House and proposes signage policies that establish criteria for signage materiality and treatment, notably:

- Policy 2.1.10.2 - Sydney Opera House signage should endeavour to maintain the use of bronze or bronze finish as an external signage material as used in the City of Sydney and The Rocks signage
- Policy 2.1.12.2 - External signage elements must use durable materials appropriate to the levels of salt and moisture in the air. Materials that do not require a paint finish or coating and that will wear with a natural patina, such as bronze, are recommended.
- Policy 2.1.12.15 - All external signage should utilise bronze (quality and type to be advised).
- Policy 2.1.2.8 - Internally, sign colours are required to relate to the context. In the case of the Auditoria Foyers, which are intended as hybrid external/internal spaces, natural materials and natural colours are required.

The recommended material for external and internal signage is bronze, as it meets the criteria as set out in this document (above). All sign types proposed in Vol. 2 are comprised of an array of one or more bronze information elements – even temporary signage.

The document supports the development of a signage strategy that derives from a system of mutually supportive graphics and sign elements incorporating bronze materiality/ colour as a dominant expression and concern for Opera House identity. Further design proposals should take note of these recommendations but note that cost, material choice and application have delayed the implementation of the proposed designs.

Document 07

Search for Suppliers of Architectural Bronze Extrusions - Specification and Recommended Supplier, Peter Clark/Hyder Consulting, 2008

A global search for suppliers of equivalent bronze material is documented with recommendations for the Opera House. Hyder consulting (structural consultants for the redeveloped Opera House Forecourt) and Peter Clark and Associates were commissioned to advise on alloy properties and subsequently to assist in the sourcing of the copper based sections required for the redevelopment. This report describes the work undertaken, the results obtained, and nominates the preferred supplier.

Document dependencies / associative material:
The document is generally regarded as a standalone document which catalogues the processes undertaken by Peter Clark and Hyder Consulting as part of the broader Forecourt redevelopment project referred to in the following:

- SOH Strategic Building Plan (2001).

Specifics relating to Bronze Componentry:
Austral Bronze, suppliers of the Austral 412, still exist, but no longer supply this product and other manufacturers have difficulty matching it. At an earlier stage difficulties had been encountered when the suppliers of copper alloy extrusions were first approached. They advised that they could not match the original alloy and offered an alternative which would not have weathered to the required matching colour.

Recommended Supplier - Only one company responded positively within the time frame available – it was recommended that Copalcor be nominated as the preferred supplier of the extrusions. A renewed search for suppliers was undertaken in order to assess newly emerged and appropriate alternatives for preferred supplier, as part of the Bronze Componentry Project.

Document 08

Forecourt Parapet Panel & Handrail Works (Stage 1) Technical Specification No: AA000416-01-B, Sydney Opera House Trust & Hyder Consulting, 2008

The document specifies a new design for the upgrade of the existing bronze barriers along the western perimeter of the Forecourt over the Lower Concourse. The revised design was developed by Utzon Architects in conjunction with Johnson Pilton Walker and Hyder consulting engineers. The work was precipitated by a failure of a section of this handrail in 2006 and required maintenance on the associated precast parapet panels. The report provides an overview of the scope of works, location of works, reference drawings, standards and codes, skilled personnel, materials, methods, design and documentation, installation verification and other comments.

Document dependencies / associative material:
Findings and the designs draw on preceding documents, including:

- SOH Strategic Building Plan (2001);
- Conservation Management Plan (2017).

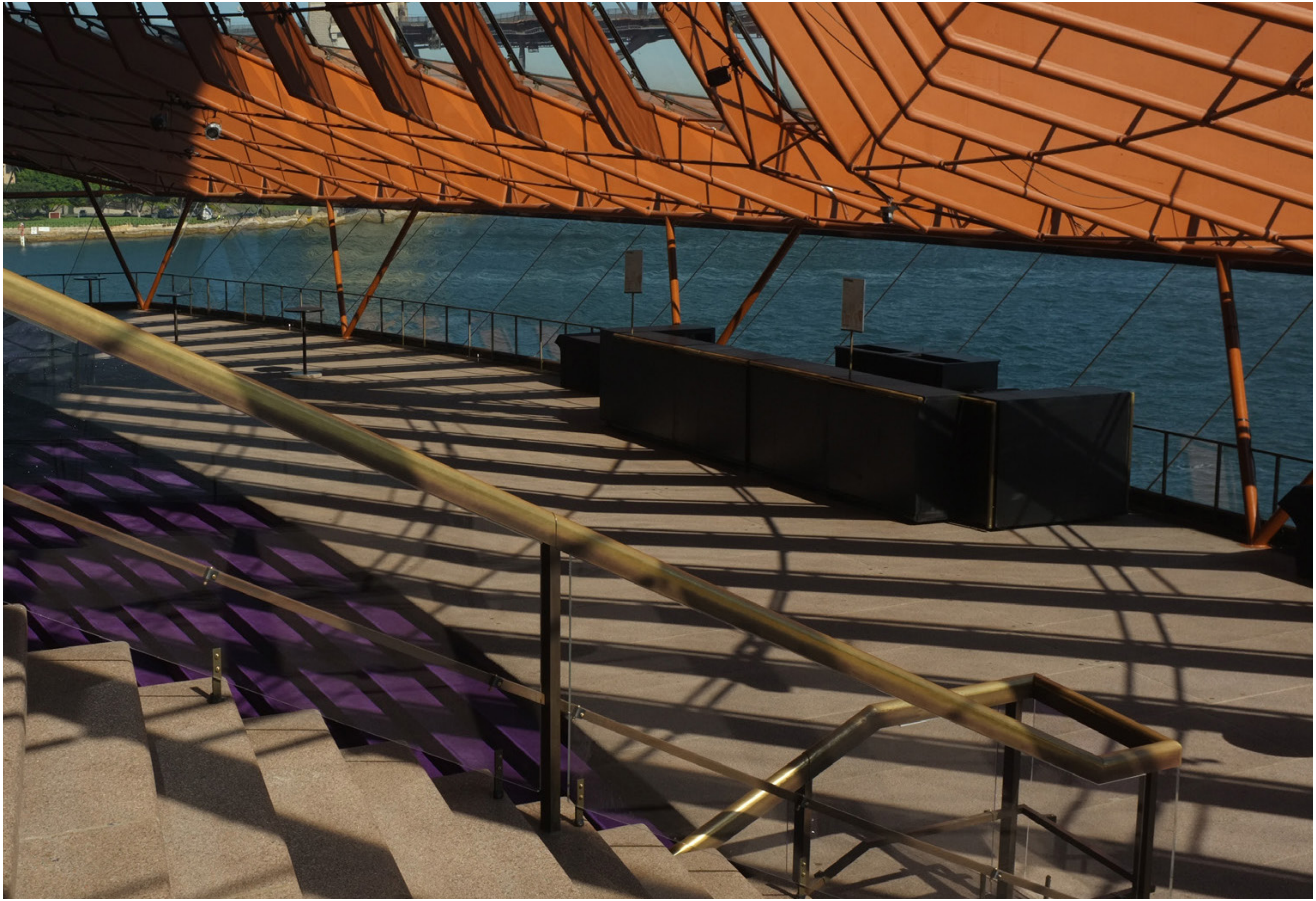
The document specifically references (and annexes) the following:

- Report on Available Suppliers of Architectural Bronze Extrusions (2008).

Specifics relating to Bronze Componentry:
Similar in appearance to the existing arrangement, the new design enlarged or thickened the bronze componentry to achieve the strength requirements necessary for contemporary design standards. New precast concrete panels were required to accommodate the increased size and fixing arrangement of the new barrier. This revised design incorporated a circular bronze handrail profile, with concealed indirect LED lighting mounted on angled bronze stays fixed into the sloping parapet. The barrier incorporated tensioned horizontal stainless steel cables which achieve compliance in this situation because of the angled configuration making them harder to climb.

Key scope of works includes (but are not limited to):

1. Removal and disposal of existing precast parapet panels, handrail and footpath finishes (performance specification) necessary to expose the existing concrete hob over the extent identified in the drawings
2. Repair and preparation of deteriorated concrete structural slab (prescriptive specification) including reinforcement corrosion related defects (e.g. spalls) within the exposed concrete elements of the existing structural slab. Repair any damage or irregularities to the surfaces of the concrete substrate that are considered detrimental to the building structure or the satisfactory application of materials covered in the other work items.
3. Design, fabrication and installation of new precast concrete parapet panels (performance specification)
4. Design, fabrication and installation of a new bespoke bronze handrail system and associated items (performance specification)



Document 09

Sydney Opera House Balustrade and Handrail Design Stage 1 Working Group Report, Sydney Opera House / Utzon / JPW, 2009

A preliminary options study undertaken to provide concept designs for handrails and barriers for the Opera House that comply with current building standards and could be developed for progressive installation across the site. The study explores technical aspects for upgrades and replacements to the existing systems of handrails and barriers. Revised handrail designs proposed by JPW comply with the dimensional requirements of AS1428.1 The greater aim of the project was to improve accessibility across the site in a manner that accords with the heritage values of the Opera House. Architecture, structure and lighting studies are addressed. Considerations include cost, durability and maintainability and sustainability. A prior photographic audit undertaken by JPW identified more than 40 handrail types in use at the Opera House, with recognition that the BCA and AS relating to accessibility have changed considerably since the installation of many of the handrails and barriers.

Document dependencies / associative material:
Designs draw on recommendations and studies of preceding documents, notably:

- Report on Available Suppliers of Architectural Bronze Extrusions (2008);
- Forecourt Parapet Panel & Handrail Works (Stage 1) - Technical Specification Report (2008).

Specifics relating to Bronze Componentry:
The scope of the report includes a review of handrails and barriers currently in use; the minimization of the number of designs to suit the needs of the site, consideration of current and anticipated compliance; heritage and accessibility requirements; concept design of railing profiles, barriers infill materials, fixings and lighting to be adapted to suit needs everywhere on the site; Access Masterplan; and preliminary design of the handrail and barriers for the new Concert Hall and Opera (Joan Sutherland) Theatre escalators.

Major focus of the architectural design was to progress design work for the new Concert Hall and the Joan Sutherland Theatre escalators as part of the Accessibility & Western Foyers Project. The design was designed as an integrated system that will be suitable across the building and reduce the number of railing types to a minimum, for consistency and to reduce cost. Six types were identified for future application and consideration with regard to existing fixing points, details of brackets and other structural support. Components include railing profile, barriers infill materials, spacing and style of fixings and lighting, are considered in light of heritage, accessibility, architecture, structure, lighting, compliance, maintenance, security, material availability, sustainability and cost. Australian Standard AS1170.1 requires that areas that are susceptible to overcrowding should be designed to support a C5 ‘crowd’ loading of 3 kN/m; and that barriers and handrails within internal circulation spaces resist a ‘C3’ live load of 0.75 kN/m.

The preferred solution identified for handrails, where required, was to install LED strip lighting into the railings, modified to include glare controlling louvres.

The document has a key focus on accessibility and ease of use, compliance and heritage, concentrating on the look and feel of railing shapes, comfort of the railings, lighting coverage and glare. Highlighted issues for future consideration included the direct visibility of light sources on steps.

The document identifies the retention of bronze componentry as critical for heritage conservation, acknowledgement that existing bronze ‘Austral 412’ is in short supply and possible alternatives should be investigated further with respect to optimal base colour and patina, long term durability, appearance and economics.

Further work for Stages 2& 3 with scope for handrail and barriers included design work for the Concert Hall and Joan Sutherland Theatre escalators and, subject to funding, the stairs from the Vehicle Concourse to the Box Office Foyer. Further stages were never undertaken.

Document 10

Sydney Opera House Handrail and Balustrade Masterplan, NSW Government Architects Office, 2014

The ‘Handrail and Balustrade Masterplan’ document was prepared in 2014 by the Government Architect’s Office which identified more than 40 existing types of handrail and barrier designs. It establishes assessment criteria for handrail/barrier replacement and proposes a sequence for upgrade. A visual inventory organising handrails/barriers into types based on profile and use was prepared.

Document dependencies / associative material:
This document builds on previous work documented in:
- Access Strategic Plan - 2013-2015 (Sydney Opera House Trust)
- Balustrade and Handrail Design - Stage 1 (2009)
- Balustrades and Handrails Design Investigation Report - 2009 (Utzon Architects + Johnson Pilton Walker)
- Existing Handrails and Balustrades Photographic Audit - 2009 (Johnson Pilton Walker)
- Balustrade and Handrail Lighting Design Report -2009 (Steensen Varming)
- Access Masterplan Development -2008 (Sydney Opera House Trust)

This document refers directly to the following:
- SOH Strategic Plan (2001);
- Utzon Design Principles (2002).

Specifics relating to Bronze Componentry:
Through assessment of compliance issues identified in the inventory, a series of priorities were developed for the different handrail and barrier types. These priorities are categorised in terms of high, medium, low or none, providing an indicative order or sequence for handrail and barrier upgrades.
The handrails identified of greatest priority are on the podiums and within the Northern Foyers where a fall height of greater than 4m exists and handrails are in the most public location. Temporary acrylic infill has been applied to these handrails which detracts from the overall aesthetic and an alternative design should be implemented.

The document precedes the 4th Ed of the SOH Conservation Management Plan and policies included in the review have been superseded. Design requirements should refer to the newest edition of the CMP (4th Ed.).


EXIT

Document 11

Sydney Opera House Building Renewal, Sydney Opera House, T. Sloane and L. Smith, 2015

This document identifies a comprehensive programme of works required to be undertaken by the Sydney Opera House in order to meet the changing nature of the Opera House in contemporary Australia. The document identifies 27 projects with a proposed staging and implementation ambition to transform the Opera House over the next 10 years. There are three stages in the strategy:
Stage 1 consists of 16 building projects, 3 building studies and 4 enabling projects. Stage 2 includes 9 building projects and 1 building study, and finally Stage 3 includes 2 building projects and 2 building studies.

(Note the Bronze Componentry Project only describes Stage 1; Stages 2 and 3 are omitted.)

The document serves as a clear outline of the intentions of the house in developing renewal through current funding, with clear ambitions for further stages yet to be announced or published.

Document dependencies / associative material:
This document is guided by the following key documents:

- SOH Strategic Building Plan (2001);
- Utzon Design Principles (2002)
- Conservation Management Plan (2017).

Specifics relating to Bronze Componentry:
The document relates to the four physical building projects included within the Stage 1 Building Renewal programme. There are a number of instances in which the document interfaces with handrails and barrier works, as well as other bronze componentry across. In particular these include:

Project 1.2 Concert Hall:
This project involves improvements to access which will require the installation of handrails from Doors 1 and 8 to seats in the choir stalls, and from Doors 7 and 14 to seats in the top circle.

Project 2.3 Under the Stairs & Project 2.4 Entry Foyer:
The activation of this area is likely to include bronze componentry that will require coordination and alignment with the Bronze Componentry Project.

Additionally, other enumerated projects such as Project 2.7 Creative Learning Centre & Project 2.9 Function Centre should be closely monitored for interfacing works embedded within emerging design proposals.

Document 12

Sydney Opera House Accessibility Masterplan, Scott Carver Architecture and Design, 2015

The Sydney Opera House Trust (SOHT) is committed to implementing the NSW Government Disability Policy Framework, which came into effect on 1 May 2011. The SOHT developed a Renewal Framework to guide the renewal and transformation of the Sydney Opera House over the next decade. Renewal will involve a range of projects that cover all aspects of the Opera House including theatres, front of house, back of house and proposed new developments. The Accessibility Masterplan (AMP) strives to ensure the SOHT achieves compliance and heritage obligations, as the Opera House is a state-, national- and World Heritage-listed architectural icon. As a key document to inform the renewal works, the AMP sets out to establish briefing requirements and feasibility level concept design for accessibility solutions.

Document dependencies / associative material:
The Accessibility Masterplan is a key step in the Renewal Framework and as such is integrally linked to:

- Sydney Opera House Building Renewal (2016).

This document provides a direct reference for the following:

- Joan Sutherland Theatre Accessibility Upgrade Project (2016).

Specifics relating to Bronze Componentry:
The AMP proposes a number of key accessibility upgrades grouped around the venues and the established Renewal Projects that represent a significant part of the Opera House improvement ambitions.

Current challenges include:

- Stairs across the site, which often have a handrail to one side only (rather than on both sides) and/or do not extend past the first and last riser of the stair which is non-compliant with AS1428.1; the height to top of stair handrails from the step tread varies over the stair flight; generally have a profile non-compliant with AS1428.1; stairs have no TGSIs or step nosing installed to assist people with vision impairment;
- Journey from SOH Car-Park to the Building– Lower Concourse level - the connecting ramp from car park has no handrails, no TGSIs, non-compliant with AS1428.1;
- Back of House Passenger Lift 12 and Lift 22: there is no internal handrail adjacent to the internal lift control panel; handrails are required, complying with the provisions for a mandatory handrail in AS 1735.12; and
- Theatre Seating - Construction and installation of temporary platforms (and barriers if required) in order to comply with the spatial requirements of Part 18.3 of AS1428.1

The design resolution of stairs; including handrails, barriers, nosings and tactiles are to be carefully considered against heritage and ensure a precinct (or global) approach. Nosing and contrast might require interpretation with a lighting solution. It was recommended that one design firm be engaged to undertake a global solution for review with the Eminent Architects Panel, DDA Consultant and Heritage Architect.
The document enumerates a number of projects with specific reference to handrails and barrier works, as well as other bronze componentry across the site. In particular these projects aim to address access issues that include:

- Project 76 - New Lower Concourse access - ramp - handrails for an accessible access ramp were proposed as part of the Opera House Visitor and Interpretation Centre (2013) undertaken by Scott Carver Architects;
- Project 72 - pedestrian ramp upgrade/Project 70 - Opera Kitchen - ramp upgrade - The proposed upgrade includes new handrails, barrier and compliant tactile indicators;
- Project 68 - Opera Kitchen - ramp upgrade - demolish redundant handrail - install new compliant handrails and tactile indicators ;
- Project 71 - carpark access upgrade - existing ramp to the Lower Concourse has a steep gradient, excessive length between landings, no handrails, and no TGSIs; upgrade includes new handrails and TGSIs compliant with AS1428.1;
- Project 73 - forecourt access upgrade - path has a non-compliant barrier, no directional TGSIs, and is obstructed by the existing bronze lampposts;
- Project 82 - taxi drop off - the footpath has a steep gradient, no landings, no handrails, and no TGSIs; and
- Revised balustrade designs have been proposed by JPW which comply with the dimensional requirements of AS1428.1.

Document 13

JST Accessibility Upgrade Project, Scott Carver, 2016

This document reflects the Sydney Opera House's commitment to implementing the NSW Government Disability Policy Framework. The Opera House seeks to improve access to the Joan Sutherland Theatre (JST) while it is closed for the JST Theatre Machinery Project in 2017.

As a part of the accessibility works it is proposed that the following be undertaken:

- Enabling improved corridors and lift access to the Northern Foyer and intermediate levels of the theatre;
- Providing additional accessibility seating to the theatre;
- Improving the provision, functionality, aesthetics and visibility of surtitles;
- Installing NCCA compliant handrails; and
- Providing accessible toilet amenities to the Northern Foyers.

Document dependencies / associative material:
This document directly refers to, and compliments work identified and set out in the following:

- SOH Accessibility Masterplan (2015).

Specifics relating to Bronze Componentry:
The document outlines design work that will be shortly undertaken within the Opera House that requires handrails and other bronze works in the following areas identified:

- New barriers - 1200mm accessible path of travel for front access & 1500mm accessible path of travel for rear access & 15 possible accessible seats with partner / assistant seat adjacent.
- Project 62 (1 Wheelchair) – new stairs with handrail, removable brass barrier H 750mm
- Project 62 (5 Wheelchairs) – new stairs with handrail, removable brass barrier H 750mm
- Project 49 - Northern Foyers access upgrade Level 2 passages finishes – walls - bronze fixture (door jambs, kick plate, and general fitment), bronze lining (lift);
- Project 49 - Level 2 passages finishes– floors - bronze tactile flooring, bronze nosing inset for stairs;
- Project 49 - Level 3 passages finishes option 1 – walls - bronze fixture (door jambs, kick plate, and general fitment), bronze lining (lift); floors - bronze tactile flooring, bronze nosing inset for stairs;
- Project 49 - Level 3 passages finishes option 2 (lift 8 upgrade) – walls - bronze fixture (door jambs, kick plate, and general fitment), bronze lining (lift), floors - bronze tactile flooring, bronze nosing inset for stairs
- Project 1 Lift 8 – new lift considerations and fixings
- Project 56 – Lift 31– new lift considerations and fixings.

(Note that throughout the document, new handrails are sometimes specified as brass.)

Document 14
Conservation Management Plan, 4th Edition, Alan Croker, 2017

The Sydney Opera House Conservation Management Plan builds on the work prepared in 2003 by James Semple Kerr. It provides the key policy framework guiding future management of the Opera House. The Conservation Management Plan (CMP) notes the necessity for the Opera House to grow and evolve, without loss of integrity; to treasure, conserve and renew. This statement encapsulates the tension in managing the Opera House. Resolving this tension to achieve a finely tuned balance between conservation and retaining functional performance, with its focus on excellence, is the subject of this document. This, the Fourth Edition, revises and updates the history and significance of the Opera House and considers recent changes within the Opera House and its precinct.
It has been extended to cover issues and areas not fully addressed previously and to anticipate future development, refurbishment and maintenance works.

This version covers the following:
- A chronological history of the Opera House (to 2014);
- An assessment of the cultural significance, including the architectural narrative, the structural rationale, the use of Bennelong Point and the significance of heritage;
- A summary of significance, including world heritage listing; and
- A comprehensive conservation policy.

The purpose of the Conservation Policies is to provide guidance for the ongoing care, use and management of the Opera House, including any changes or development.
The intention of the policies is to retain, and where possible reinforce, the significance of the place, including its use as a contemporary performing arts centre. The document not only lists the policies for development, but it also provides a comprehensive chronology for the development of the Opera House, its significance and legacy. Part 1 of the CMP serves as a meaningful reference document establishing the key elements, contributors and narrative. In principle, this document may be updated as and when required to complete its listing of current and ongoing changes to the Sydney Opera House. New editions will be created as change necessitates.

Document dependencies / associative material:
This document is the latest edition of the CMP and provides a foundation for all current and previous studies, reports, and projects associated with the Opera House since its publication. It's policies are comprehensive and forthright nature, taking as their own foundation the following documents:
- SOH Strategic Building Plan (2001);
- Utzon Design Principles (2002);
- Conservation Management Plan, Ed. 3 (2013).

Specifics relating to Bronze Componentry:
The document enumerates a number of projects with specific reference and relation to handrails and barrier works, as well as other bronze componentry. In particular these projects aim to address access issues that include:

Policy 7.10 – Bronze in glass walls and louvres.
The existing bronze metalwork must be:
- Retained and conserved;
- Fixings and adjacent metals must be compatible with the bronze, both chemically and visually; and
- Oxidation or other visible damage must be removed in accordance with Policy 18.11.

The present glass wall structure, designed by Peter Hall and Arup, is of painted steel with bronze trim externally. Utzon's original intention for glazed infills to these areas could be reconsidered as part of a redesign of the glass wall system. Any redesign of the system must retain a bronze of an appropriate alloy as the externally exposed material.

Policy 7.12 – Bronze framing in opernings.
Openings across the Podium must retain their original unpainted bronze joinery and finish, and any new joinery should match it. Bronze elements include:
- Bronze framed glass to openings in Podium;
- Bronze vehicle doors to the central passage: configuration may change but bronze must be used.
- Lower Concourse - Bronze framed poster vitrines and doors: use of bronze is important to maintain.
- Four bronze entrance doors to stairways and lift including back-lit cut out signs: consistent use of bronze is important.
- Bronze framed Stage Door with back-lit cut out sign: consistency of material with other doors is important.
- Bronze vehicle door to the Central Passage: use of bronze is important.

Policy 7.14 – Monumental Steps.
The Monumental Steps must remain open and free of any obstruction, except for the bronze rails on their east and west edges. Any alteration must retain their existing materials, profile and configuration.

Policy 7.18 – Precast paving and cladding system.

Bronze fixings and concealed drainage must be retained and conserved. When repair or replacement takes place, care must be taken to maintain quality control of colour, dimensions, form, finish and details, including fixings to match existing fabric.

Policy 7.19 – Bronze railing system.
The material and open design of the original bronze railings and balustrades across the site are a unifying element and must be retained. If any railings are required to be reconfigured to address accessibility, safety or security issues, the revised design must retain the following:

- Bronze material of the same alloy as the original rails, or similar alloy with the same colour and properties;
- Limited related range of simple geometric handrail and balustrade sections and configurations, appropriate to the application and consistently applied across the site;
- Open design with minimal obstruction of views;
- Concealed indirect lighting where appropriate, and particularly on stairs.

Podium - added acrylic panels to lower part of guardrails:
- Explore alternatives to address safety issues as part of review of all handrails and guardrails.

Podium - radial palisade fencing introduced where the northern ends of the Podium decks meet the external steps:
- Explore less intrusive design of safety railing with minimal impact on views.

Broadwalk - bronze handrail system around perimeter:
- Handrail profile and configuration may be altered as part of handrail upgrade across the site, but angled configuration must be retained. Retain the use of bronze for handrail system and ensure minimum visual impact.

Stairs and lift from Covered Concourse - bronze handrail system with concealed strip lighting:
- To be considered as part of overall approach to handrails across site. Safe lighting of stairs is essential.

Southern and Northern Foyers - inverted ‘U’ section bronze handrail system to stairs:
- Consider any changes only as part of overall approach to handrails across site. Posts should be minimised. Minimal visual obstruction below handrail is most important, allowing rails to reinforce stair geometry.

Southern and Northern Foyers - square section bronze guardrails at base of glass walls (1973):
- Any changes should retain minimal section size and minimal impact on views.

The Studio - bronze material used for handrails and hardware:
- Use of bronze is important. Configuration should relate to others on the site in similar situations.

Concert Hall, Joan Sutherland Theatre - bronze fittings generally, including tapered and angled guardrails to boxes and circle, stair lights and door hardware:
- Bronze as the primary material is the most important factor. These should be considered as part of a site-wide study on bronze handrails.

Stairs and lift from Covered Concourse - bronze handrail system with concealed strip lighting:
- To be considered as part of overall approach to handrails across site. Safe lighting of stairs is essential.

Drama Theatre, The Playhouse, Function Centre - painted steel handrails:
- Should be changed to be consistent with other bronze handrails.

Policy 14.4 Forecourt, Broadwalk, Podium steps and Lower Concourse lighting. Utzon’s preference was for concealed and indirect light sources, both internally and externally, and at the time the Opera House was designed and built, relatively low lighting levels were deemed acceptable in outside areas. Any adaptation or alteration of lighting to these areas must:

- Be sufficient to connect and relate the form of the Sydney Opera House to its peninsular setting, but not of a level that would compete with the illumination of the shells;
- Be sufficient to provide safe pedestrian access;
- Continue to be set at a height and so baffled that glare and distracting light spill are eliminated from the eyes of pedestrians, even when viewed from a distance;
- Retain a monochromatic light with appropriate colour temperature to render the natural colour of materials as accurately as possible;
- Be sufficient to provide adequate ambient light for activities in the Lower Concourse, but avoid light spill when viewed on approach or from surrounding areas;
- Employ the minimum equipment necessary for the job and locate it as unobtrusively as possible.

Policy 18.11 – Cleaning bronze.
Any cleaning or maintenance on the bronze, both externally and internally, should be carried out in accordance with the Lucas Stewart 2005 Report on the Maintenance of Bronze Components and as modified with the use of olive oil. The

patina of age, weathering, or use, should not be removed unless it is damaging the surface of the particular component or endangers its survival. Any potentially damaging or disfiguring oxidation or encrustations should be removed with as little damage to the patina as possible.

Additional exterior bronze elements that require maintenance include:

- 1959 bronze disc in monumental steps marking set out for major halls: must not be altered or moved.
- Bronze plaques for Writers Walk and Lewis Fountain on western side of Forecourt: could be moved or removed but use of bronze is important.
- Bronze drinking fountains: could be redesigned in same material.

Policy 18.16 – Removal of fabric.
Where significant fabric is removed and capable of subsequent re-use on site, its location must be recorded, and the items catalogued and stored safely for possible future replacement or relocation in a space of appropriate character.

Where individual original components, such as handrail or balustrade sections, are to be removed and replaced with a different form, their location and configuration must be recorded and representative sections of the original material retained, and safely and securely stored with Sydney Opera House archives in accordance with the Collections Management Strategy.

Policy 15.2 – Significant signage.
Significant original (1973) sign elements should be retained and adapted, or replaced with replicas only if required for code compliance, improved legibility, functionality or name change. These signs include:

- Bronze faced back-lit signs over entry doors in the Vehicle Concourse;
- Any other signage elements identified in the review of the Signage Manual (that include bronze elements).

Policy 18.20 – Supply of replacement material.
Replacement material should, where possible, be sourced from the same supplier / manufacturer, and use the same specifications and methods as the original to achieve an exact match, or as close a match as possible. If the original supplier / manufacturer is no longer available, a new supplier must be found who can:

- Meet the required specification; and
- Match the material and supply the required quantities.

A strategy for maintaining security and availability of replacement materials and components should be part of the Sydney Opera House Asset Management Plan or its equivalent.

Taken together, these policies and points oulined in the latest 2017 update of the CMP provide both the philosophical and practical framework for undertaking work related to the change, conservation and care of the bronze elements at the Sydney Opera House.


BAR

Chapter 2

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Opera House Storage Facility Audit

Original stock from Austral 412

A visit to the Opera House's storage facilities revealed the extent of bronze material and componentry archived and stored during the course of previous renewal works. Their physical inspection provided insights and shaped recommendations concerning materials, weathering, profiles and fabrication techniques

Original stock
Retention of the original Austral 412 bronze alloy is considered critical to maintaining authenticity. This custom alloy, developed for the Opera House, is no longer available. Recent works have relied on alternative alloys, most notably the Forecourt Parapet Handrails (2008-9) where the alloy C68700 was supplied. In the time since project completion, this alloy has been classified as inactive and is no longer available.

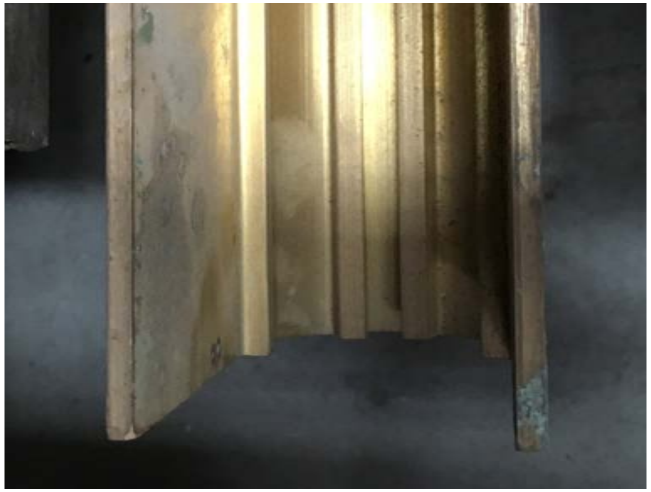
There are two possible procurement avenues for Austral 412. The first is to find an alternative alloy that is currently active and available globally; one that achieves similar corrosion resistance and extrusion, forging and brazing properties to those of Austral 412. The second avenue requires the commission of a foundry to develop the Austral 412 Alloy to its original specification. This is feasible due to the scale and scope of architectural bronze required for the project. Both options were assessed by the Renewal Team. following a separate tender for the procurement of billet and its extrusion and tooling.

Given the large quantity of bronze required for the handrail and facade elements of the current renewal projects, the price to manufacture the custom alloy (Austral 412) proves to be comparable to the selection of a readily available alternative standard alloy.

Weathering
The original unweathered alloy has a characteristic yellow appearance of brass. Our work with the Eminent Architects Panel encouraged the use of chemical ageing of new architectural bronze to accelerate the ageing process, which is necessary to avoid the unsightly appearance of a patchwork of new and old bronze and brass.

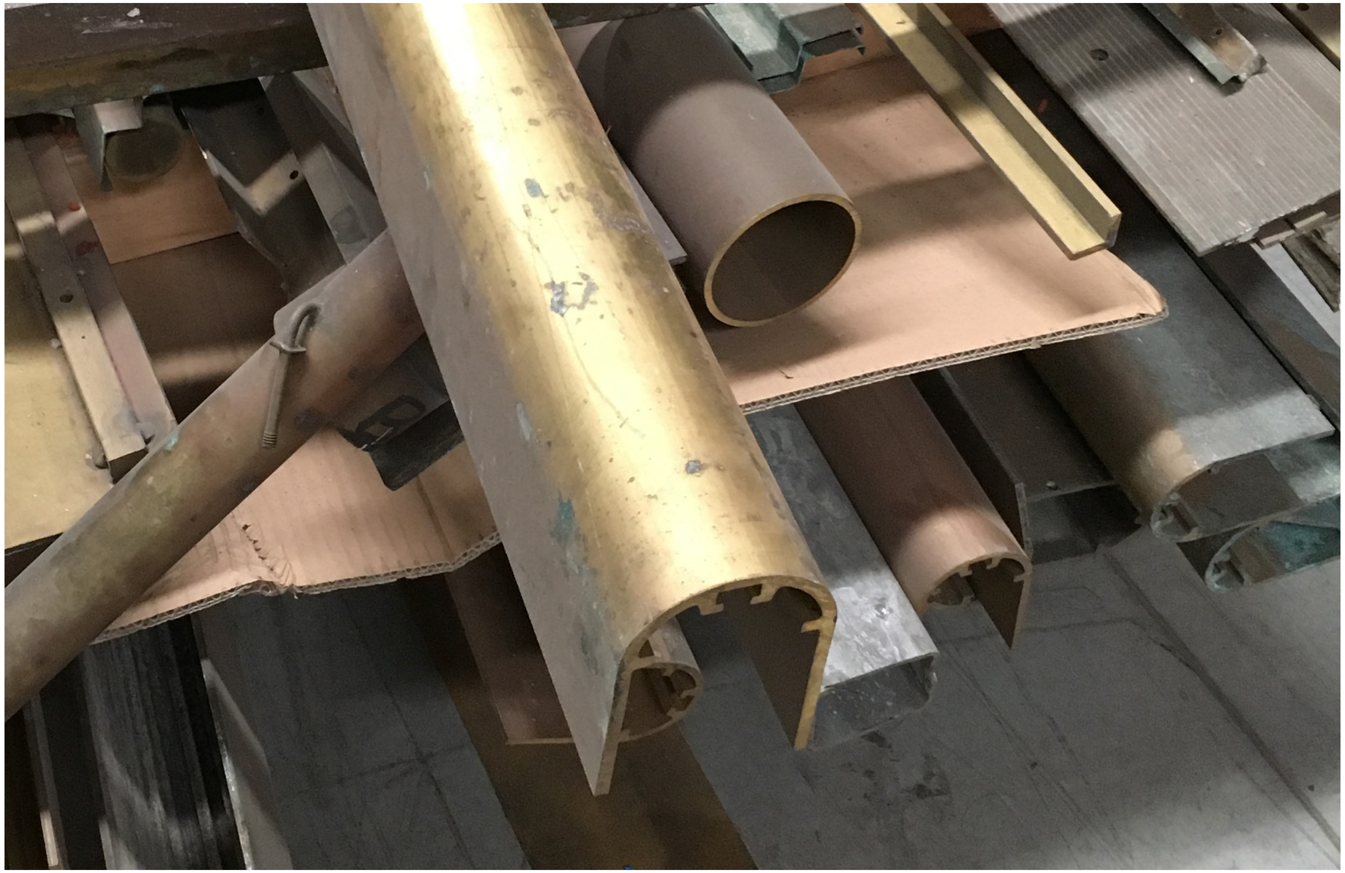
01

03

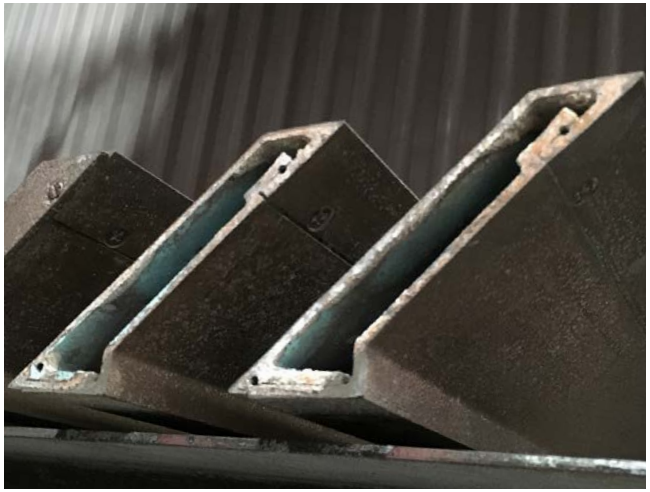


02

01 Bronze aging samples - exterior comparison.
02 Original U-Channel profile.
03 Recreated Austral 412 Bronze billet prior to extrusion.



01



03

02

01 Original extruded profiles in storage.
02 Hollow circular guard rail.
03 Louvre profile.

Profile section types

The process of extruding architectural bronze resembles that of aluminium; however the investigation of existing profiles revealed a number of constraints that must be taken into consideration.

Hollow profiles
The bronze louvre profile found at the storage facility, and shown in the image 03, at left, was produced in two sections as a result of a constraint of the die used to achieve this profile. The forces required for the extrusion process, in conjunction with the behaviour of the material and temperature as it exits the die, does not support the interior profile responsible for producing the hollow of the form.

As an alternative process, the hollow of a circular handrail can be produced via the extrusion process, through use of the mandrel portion of the die. This profile is large enough to resist the forces of the extrusion as it exits the die.

Screw flutes
To facilitate end caps and fixing screws, it is common in aluminium extrusion to include screw flutes to accept fasteners. Tolerances unique to the architectural bronze extrusion process do not allow profiles with finer details to be produced. They must therefore be accommodated in other ways.

In the louvre profile, a void to accept screws has been formed by two sections, each with a semi-circular dimple that, when combined, form the screw flute. The dimple in the die profile is small enough to resist the forces of extrusion without compromising the die life or the final profile.

Connection typologies

Welding
The welding process used in conjunction with architectural bronze is brazing. Brazing is a widely used process comprised of the following elements:

- Joint preparation;
- Flux;
- Filler material; and
- Heating.

There are many different brazing techniques, but the basic principal of soldering and brazing is one in which the workpiece is heated to above the melting point of the filler. At this point, the filler becomes molten and is drawn into the joint by capillary action. The liquid metal filler then forms a metallurgical bond with the workpiece in order to create a joint that is as strong as the filler material itself.

The filler material is typically an alloy of silver, brass, tin, copper or nickel or a combination of these. The choice of filler is determined by the workpiece material because they must be metallurgically compatible. The heating process for architectural hardware is either carried out on site, or in a workshop using a gas torch - typically oxyacetylene. A small gap of approximately 0.05 mm is necessary to facilitate capillary action during the heating process.

Note: the filler material will have a different appearance to the base workpiece for both natural and accelerated chemical ageing.

Mechanical Fixings
When architectural bronze sections are too small, brazing may result in a weak joint. When section wall thickness's are too thin for brazing, or the different appearance of a brazed joint is undesirable, then mechanical fasteners may be used to create jointed connections. Typically, mechanical fixings are concealed or countersunk, as exposed and protruding fasteners can be considered unsightly, and the shape and colour of the fixings may not match the aesthetic aims of the project.

In the image to the right (02), a brass bush has been attached to the square section of a barrier rail, with a large counter-sunk fixing. The connection to the adjacent square profile is made with a machine or grub screw. This type of connection can loosen over time and, if required to support the crowd loading of a barrier, would need to be significantly larger. This can be accommodated as larger sections are required to resist these load categories.

01

02

01 Sample of brazed joint.
02 Sample of concealed fixings.

Chapter 3

Studies

Existing stair and barrier conditions
Study 01

Any Design Manual developed for the handrail and barrier assemblies must be able to address the range of conditions across the interior and exterior of the Opera House.

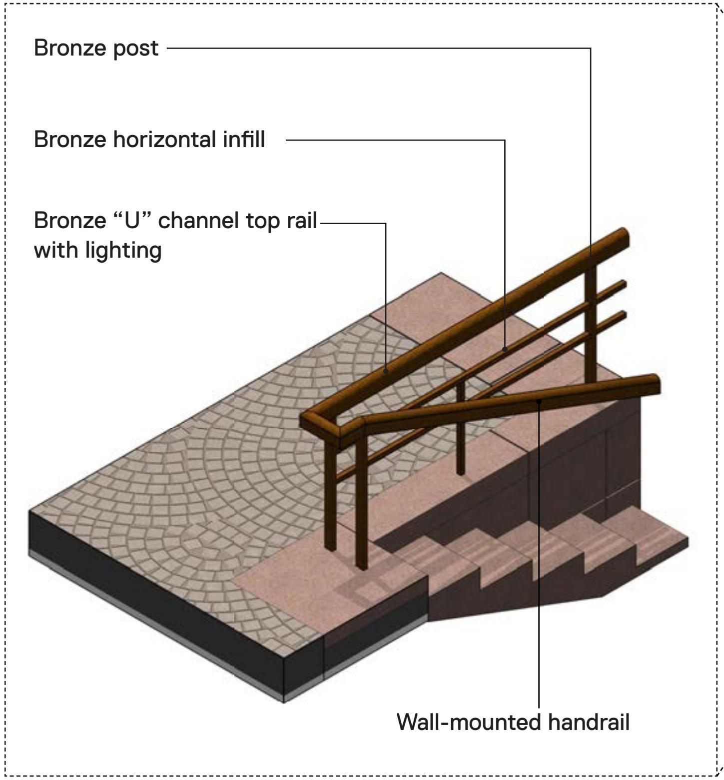
In order to assess and better understand the existing stair and barrier conditions, site measurements and photos were taken and used to produce a detailed digital model of the existing stair connecting the Western Broadwalk to the Lower Concourse. This model provided an opportunity to analyse the geometries of the handrails and relationship to adjacent materials.

The outdoor condition proves to be somewhat complex - one in which the handrail and toprail must turn from a horizontal position to an angle that can accommodate the geometry of the stairs.

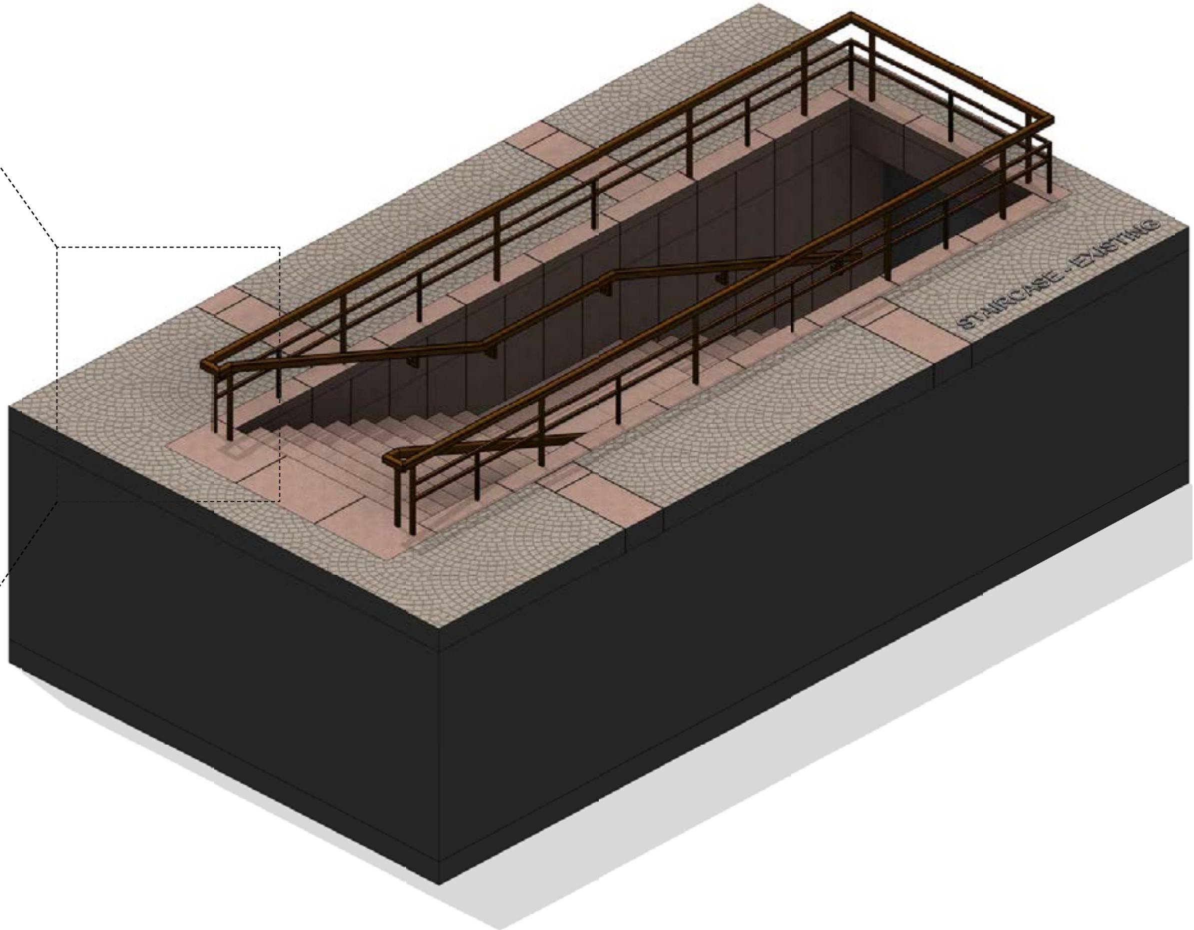

01


02

01 Bronze U-Channel top rail
02 Bronze horizontal infill.



01



02

01 Detail - stair, handrail and balustrade
02 Typical stair - isometric

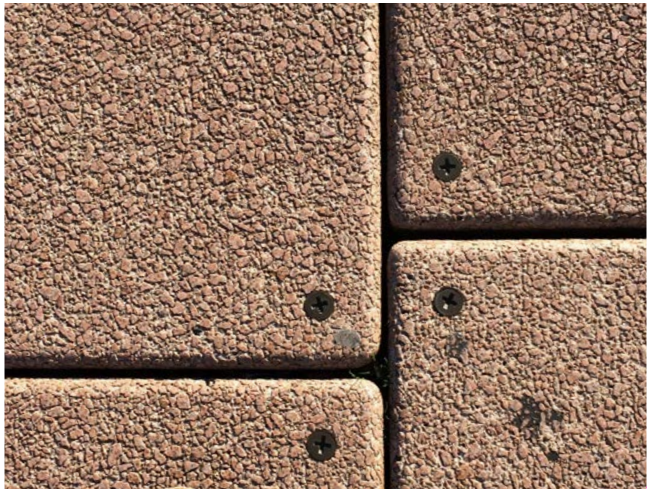
Building grid & modules
Study 02

Diagram 01 (overleaf at right) illustrates the primary; secondary and tertiary building grids. These are reflected in the Opera House's wall and floor precast panels, barriers and granite setts, both internally and on the Podium and Western Concourse.

When the building grid is not followed, it deviates very subtly and is justified by necessity. The Diagram 01 indicates where the rhythm of handrail brackets is shortened to ensure the handrail is adequately supported.

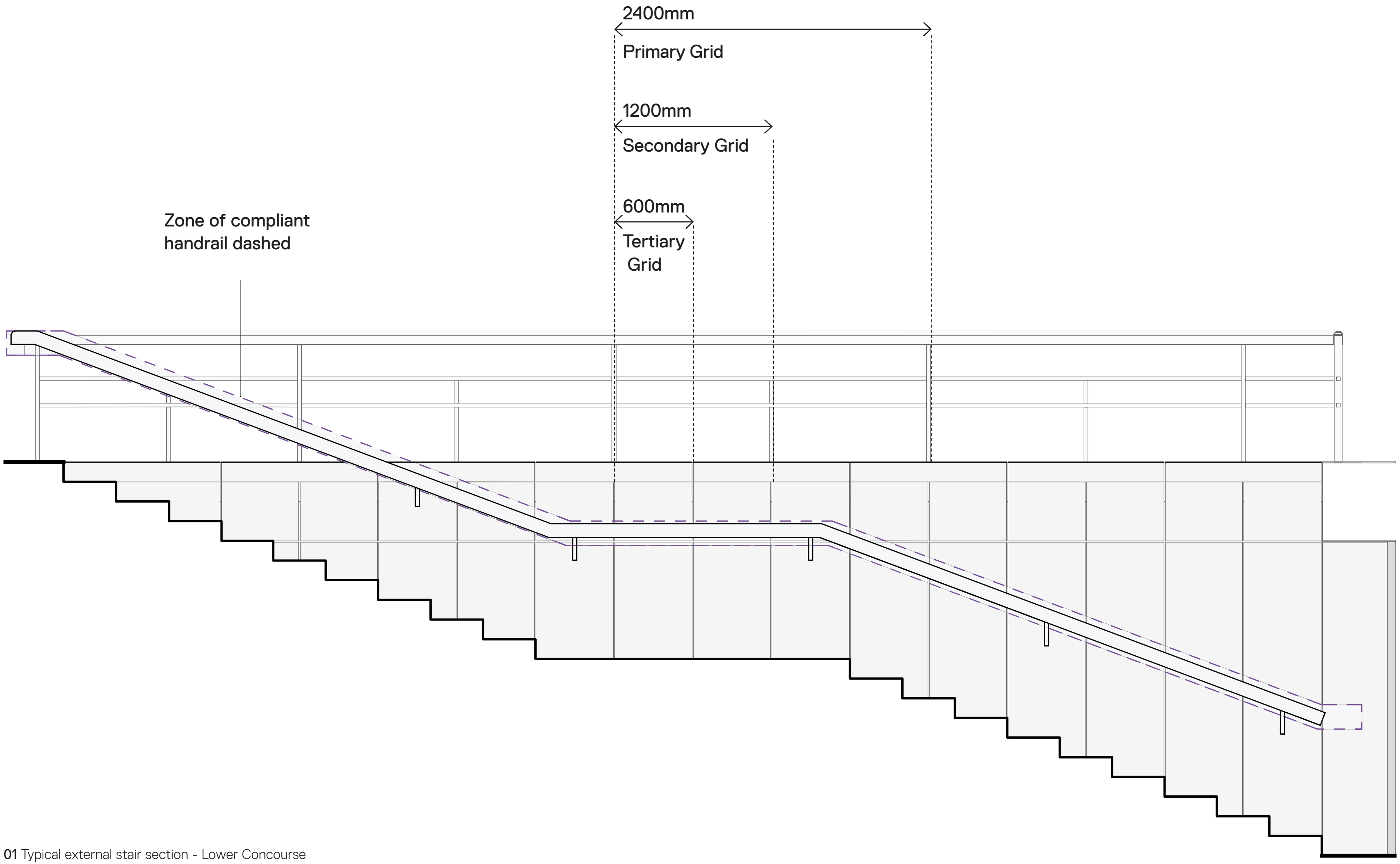
It is important for us to understand these conditions, as not all bronze sections can accommodate an increased span. Nevertheless, an analysis of the building fabric, material modularity - the pre-cast panels - and stair geometry, supported a clear relationship of the handrails to building grid. This emphasized the suitability of using the existing mounting points for future designs.

01

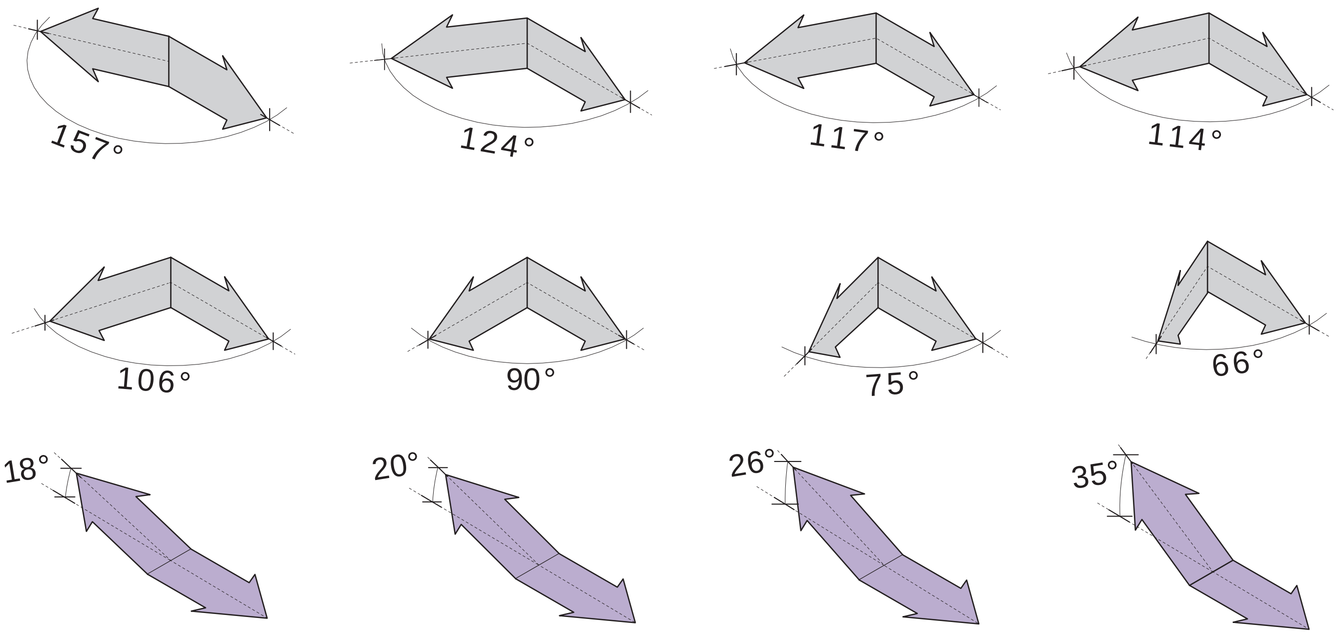


02

01 Horizontal and vertical joint.
02 Granite sett modules.



01 Typical external stair section - Lower Concourse



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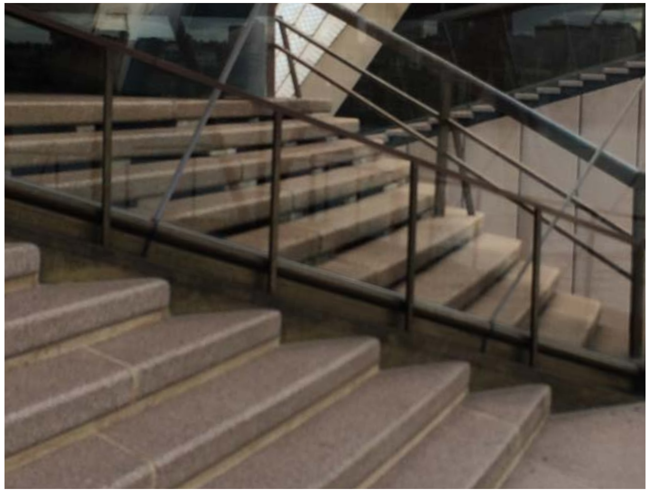
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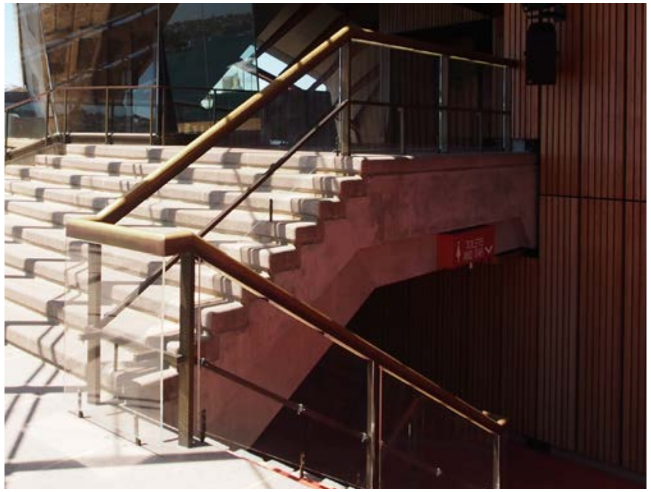

02

01 Top & middles rows - Horizontal changes in plan;
Bottom row - Vertical changes in stair geometry.
02 Stairs in the Northern Foyer.
03 Northern Foyer interior and exterior stair.

Stair and plan geometries
Study 03

In developing a flexible, universal approach for the Design Manual, future barriers should be able to accommodate the wide range of stairs and varied geometries of the Opera House.

The diagram at left (01) depicts the myriad of angles in plan and (02) vertical changes in stair and ramp pitch that were used to evaluate proposals found within the 2009 "Barrier and Handrail Design Stage 1" (Document 09). Although the initial concepts were able to accommodate changes in angle through the use of cast nodes, it was felt the large quantity and variation of castings required to do so would be cost prohibitive.

An extrusion with concealed connections would be more suitable, as exposed connections would require new post positions, in turn requiring alteration of the existing grid and new pre-cast elements, rather than the retention of the existing pre-cast elements.

Profile selection

Study 04

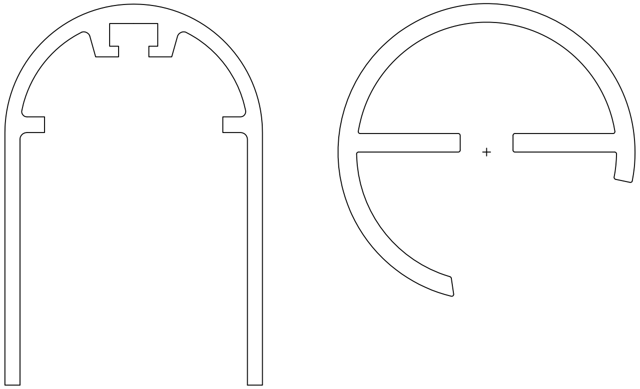
The bronze handrails are one of the principal tactile elements of the Opera House. As such, the top rail extrusion directly expresses and highlights visitors' contact with the materiality through the hand-burnished "honey" colour of the handrail, particularly visible at the termination points.

Grimshaw's approach to heritage conservation emphasises the need to maintain the dominance of the top rail, encouraging the new handrail system to tell the same story of materiality and visitors contact, as the patina is worn away.

All former design studies and the original U Shaped Profiles were checked to determine their ability to span the distances required by the building grid modules and current post locations.

Following consultation with the Eminent Architects Panel, there was a strong preference to move forward with investigations of a circular top rail profile, in lieu of the U-shaped profile or the hybrid top rail profile proposed by JPW in 2009.

01

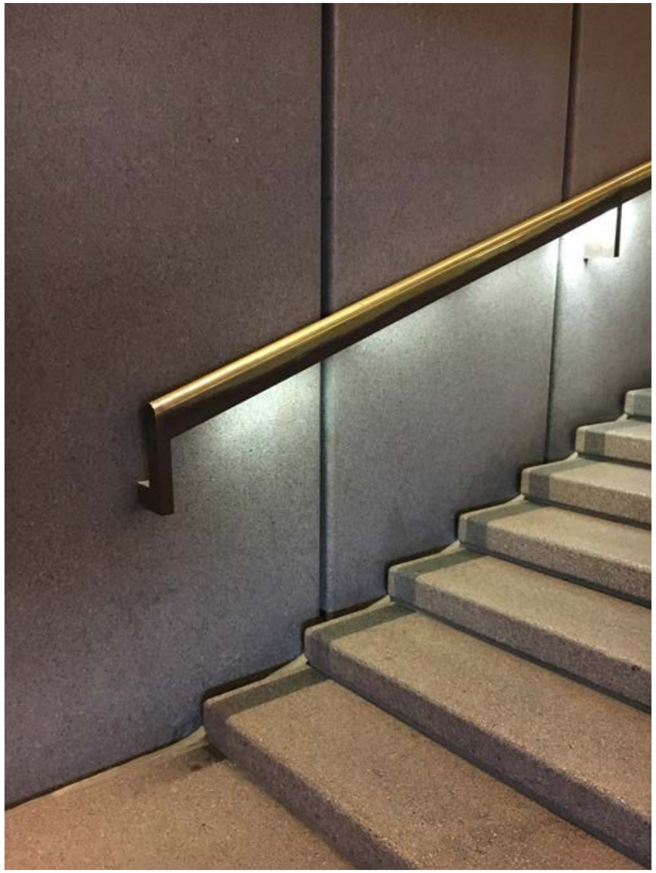


03

02

01 U-Channel section profile in situ Northern Foyer.
02 Bottom right: circular profile in situ Western Broadwalk.
03 U-Channel section profile & circular profile (80mm) top rail.

02



01

01 Existing T5 flourescent lighting.

02 Linear strip LED lighting with micro-louvre.

Handrail lighting
Study 05

The existing handrail lighting condition is composed of a T5 fluorescent baton concealed within a U-channel profile. At the time of their design, the handrail profiles were designed to accommodate the lighting technology of the day. This produced the handrail's U profile, one which is too wide to be compliant with current standards and regulations.

Additional problems related to the handrail lighting are:
- The handrails are wired in series, making fault detection difficult along the line; and
- Handrails along walls produce lighting effects that make the baton lengths visible along the vertical surface and reveal visible light breaks and jarring non-continuity.

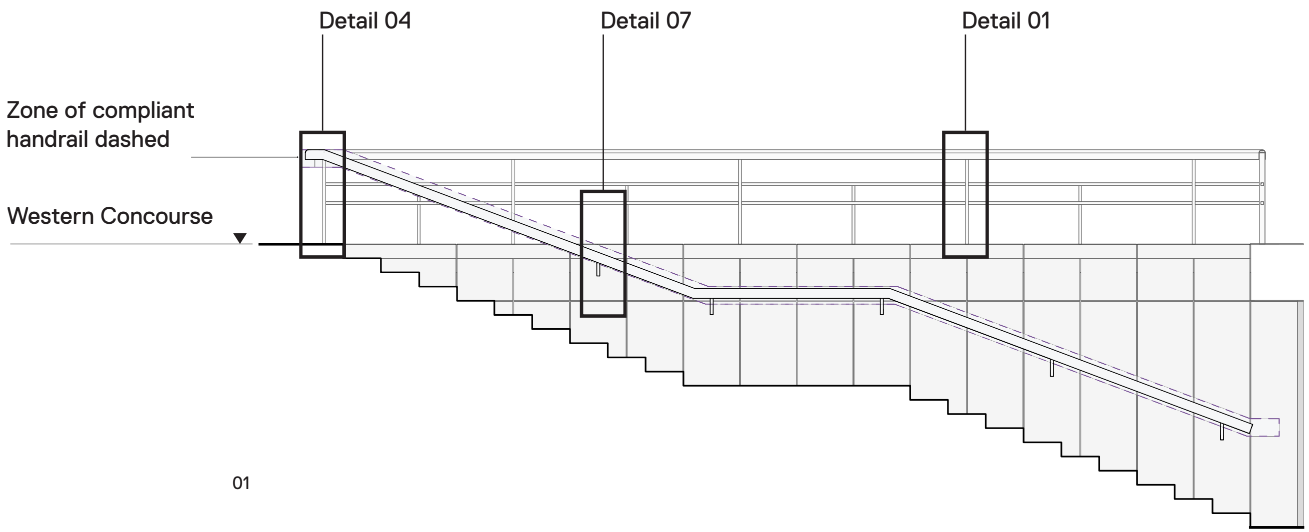
The updated, integrated lighting design will contribute to the overall lighting design for each internal and external space. New lighting will also function to provide compliant lighting levels for both accessibility and the lighting of public spaces. This is done by providing adequate levels of lighting while maximising the even distribution of light in circulation spaces and by improving the visual comfort.

Typical details - existing exterior

Study 06

The following diagrams present a series of studies undertaken of key handrail and barrier details typical of those found across in the exterior of the Opera House. These diagrams document:

- Handrail and barrier section profile types;
- Infill profiles;
- Post positions;
- Key heights, dimensions and proportions;
- Mitre angles and assembly geometries;
- Ground and wall fixings; and
- Lighting positions.



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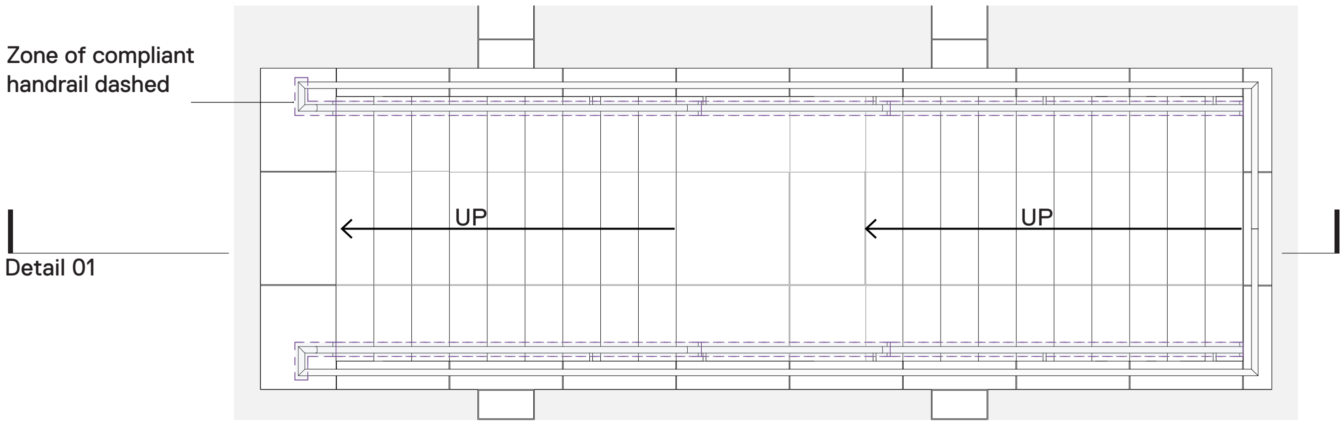
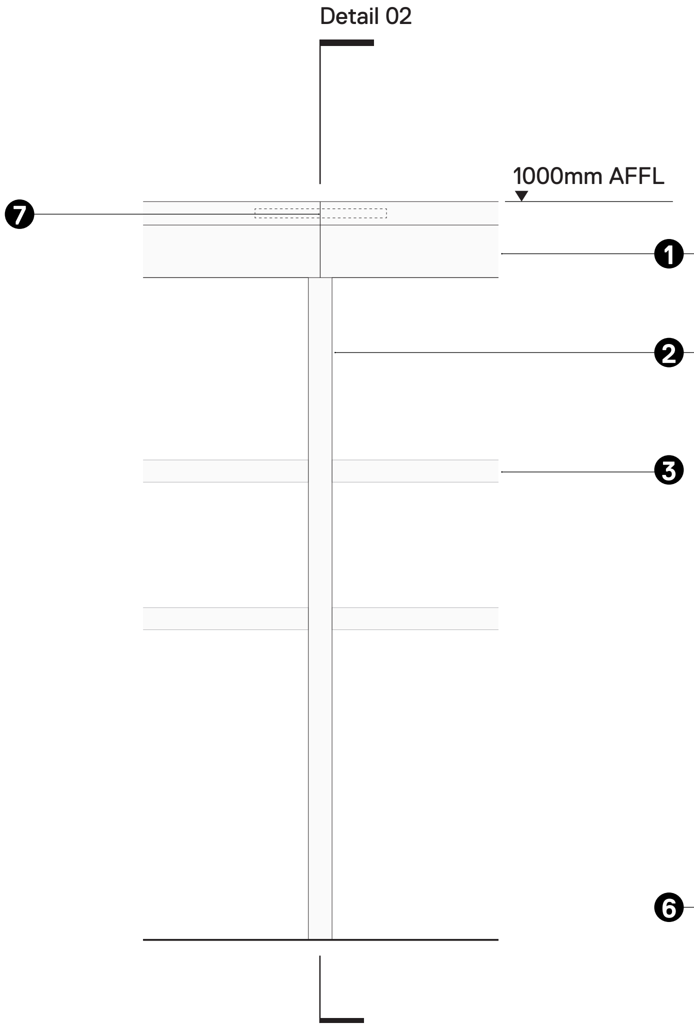


02

01 Section: typical external stair, handrail and barrier.
02 Plan: typical external stair handrail and barrier.



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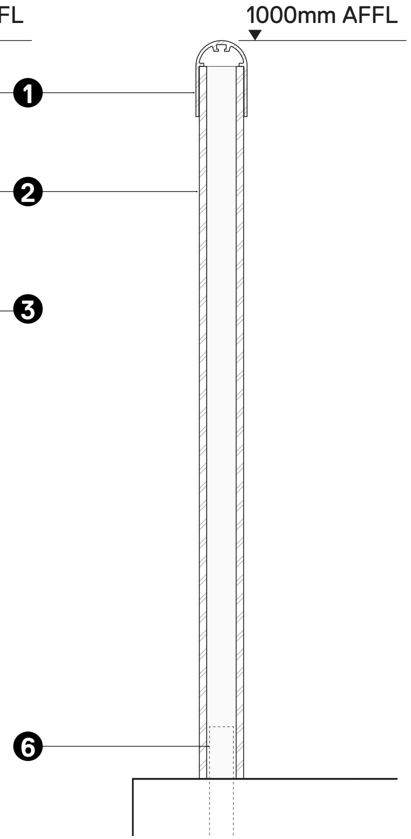

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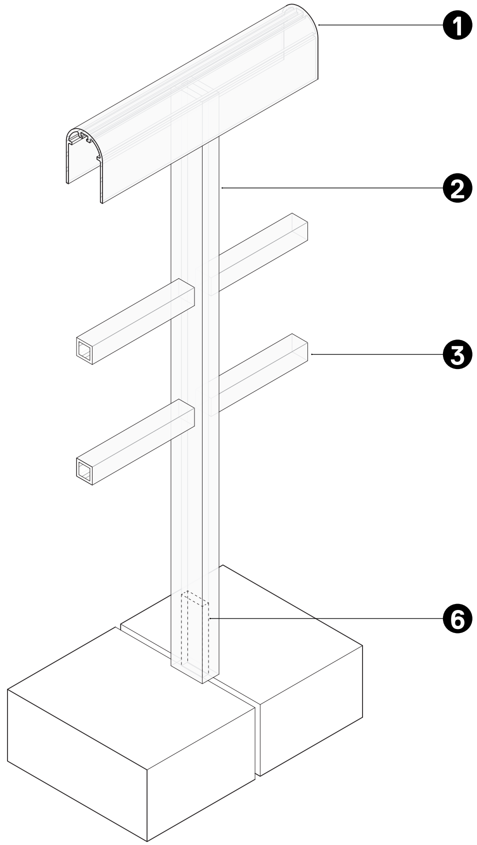


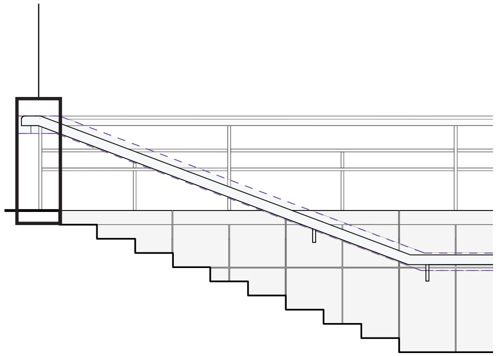
03

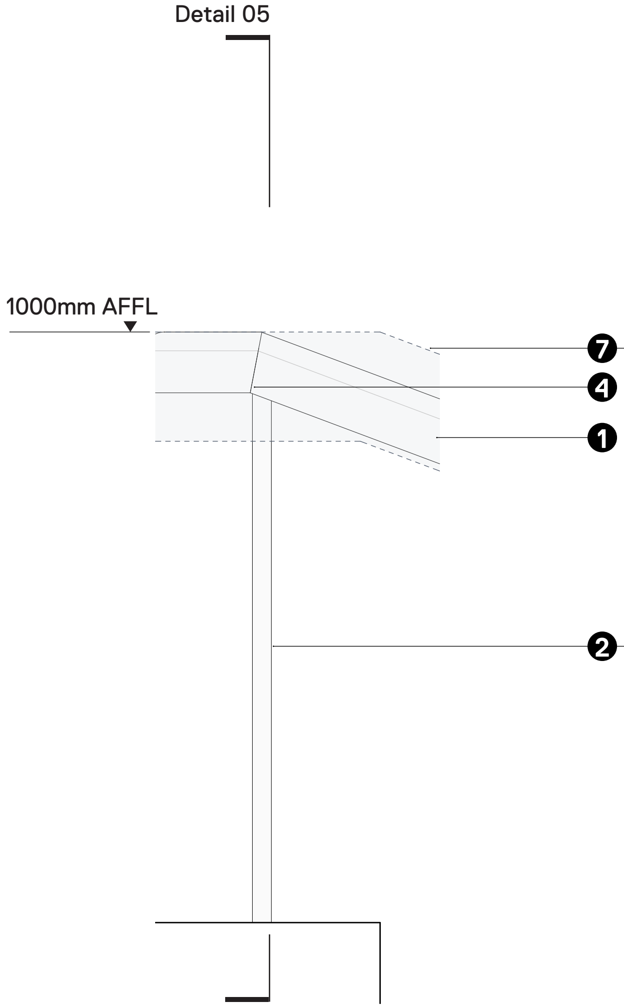
1 U Channel top profile
2 Post
3 Infill (square profile)
4 Mitred joint
5 Lighting
6 Spigot
7 Sealant joint

01 Barrier post elevation.
02 Barrier section.
03 Barrier 3D

Typical details - existing exterior

Study 06





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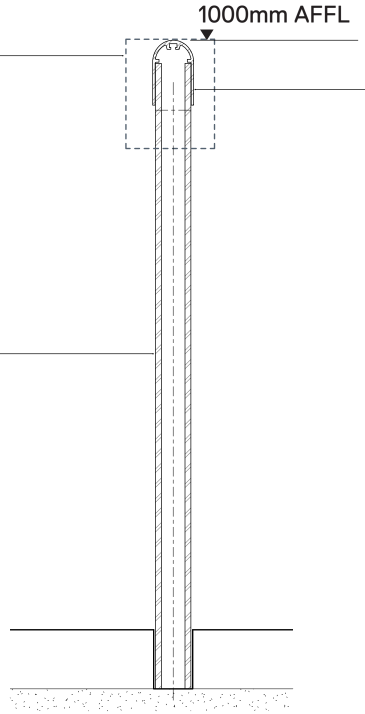
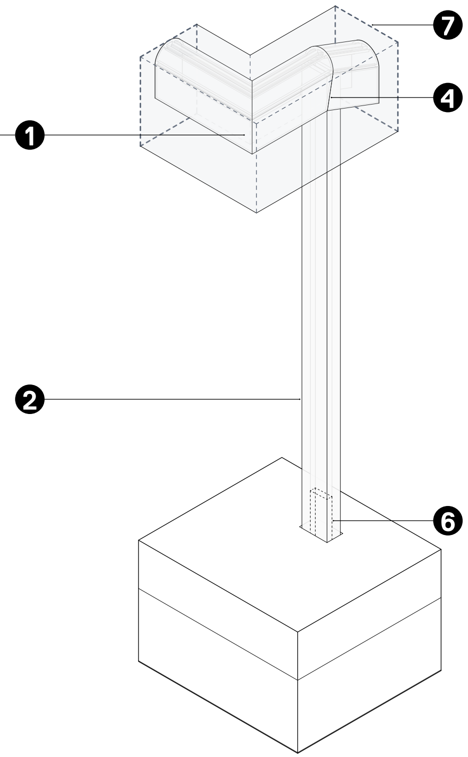


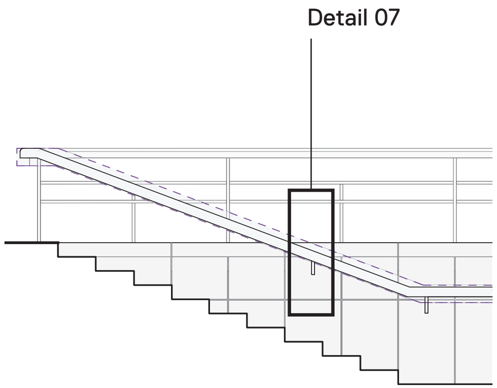
05

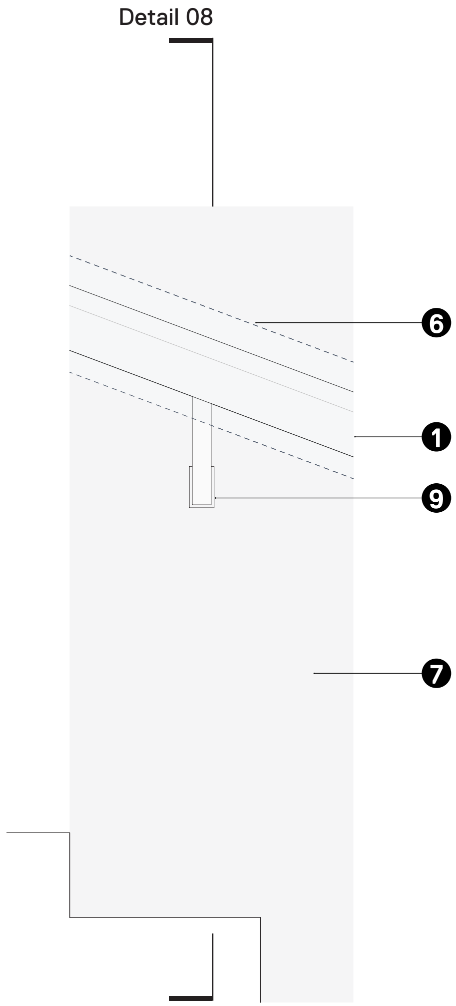


06

- ❶ U Channel top profile
- ❷ Post
- ❸ Infill (square profile)
- ❹ Mitred joint
- ❺ Lighting
- ❻ Spigot
- ❼ Zone of compliant handrail dashed

04 Barrier post elevation.
05 Barrier section.
06 Barrier 3D.





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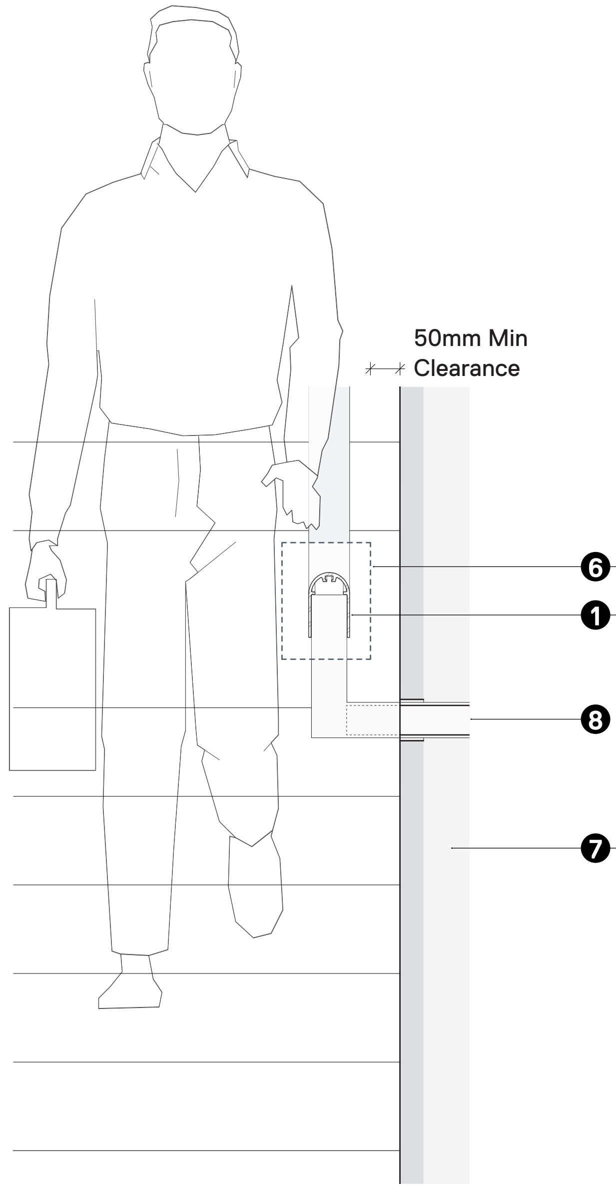

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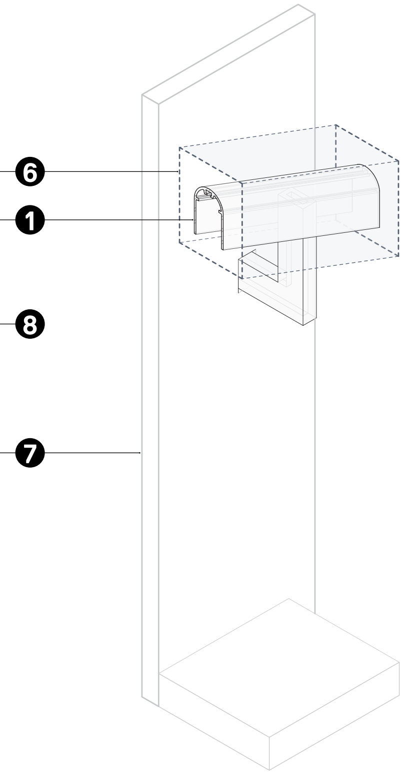


09

1 U Channel top profile
2 Post
3 Infill (square profile)
4 Mitred joint
5 Lighting
6 Zone of compliant handrail dashed
7 Pre-cast granite sett
8 Spigot through pre-cast granite sett
9 Handrail brackets always vertical

07 Wall-mounted handrail partial elevation.
08 Wall-mounted handrail section.
09 Wall-mounted handrail 3D.

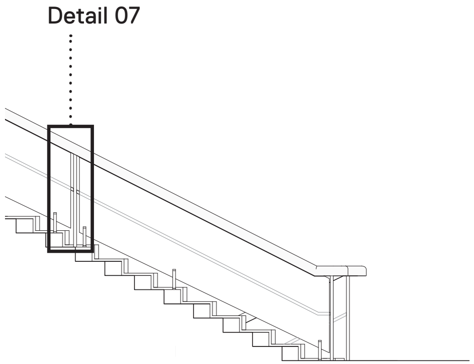
Typical details - existing interior

Study 07

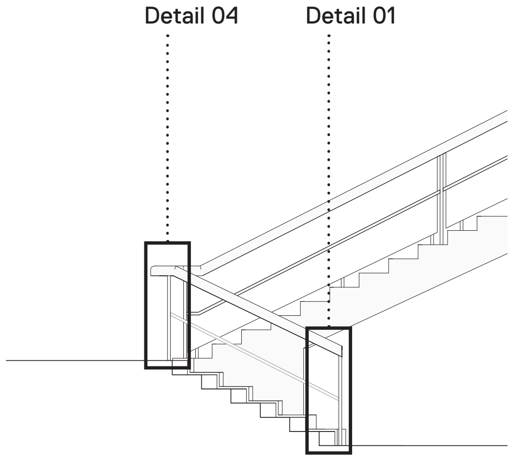
The following diagrams present a second series of studies undertaken of key handrail and barrier details typical of those found across the interior Northern Foyer of the Opera House. These diagrams document:

- Handrail and barrier section profile types;
- Infill profiles;
- Post positions;
- Base plate positions
- Key heights, dimensions and proportions;
- Mitre angles and assembly geometries;
- Ground and wall fixings; and
- Lighting positions.

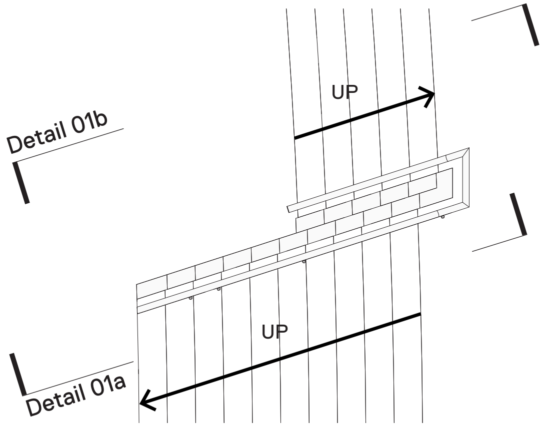
Taken together, the details demonstrate the limitations of the current profiles with respect to accomodating changes in angle in elevation and in plan.



01a



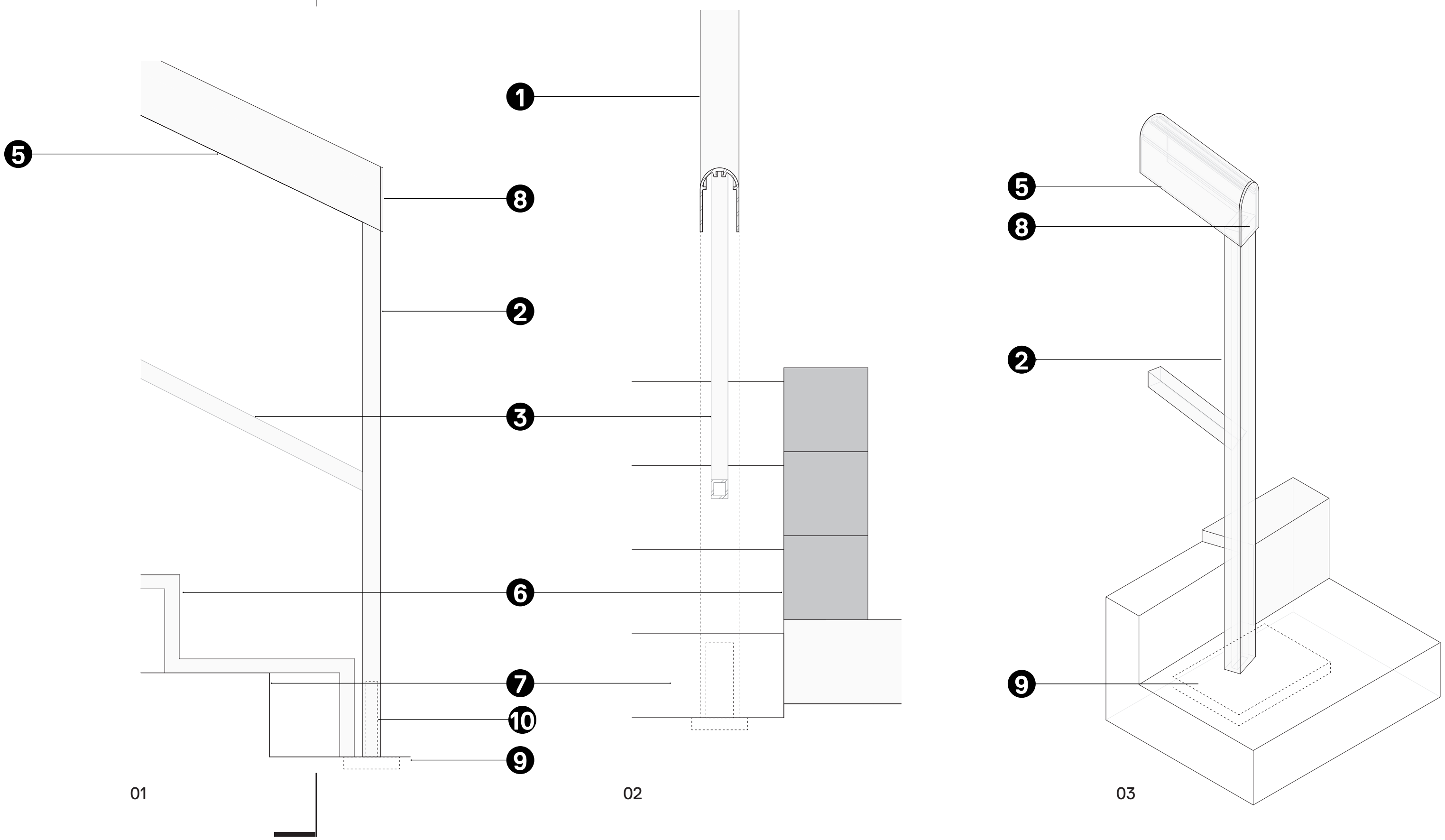
01b



02

01a-b Section: typical internal stair, handrail and barrier.
02 Plan: typical internal stair. handrail and barrier.

Detail 02



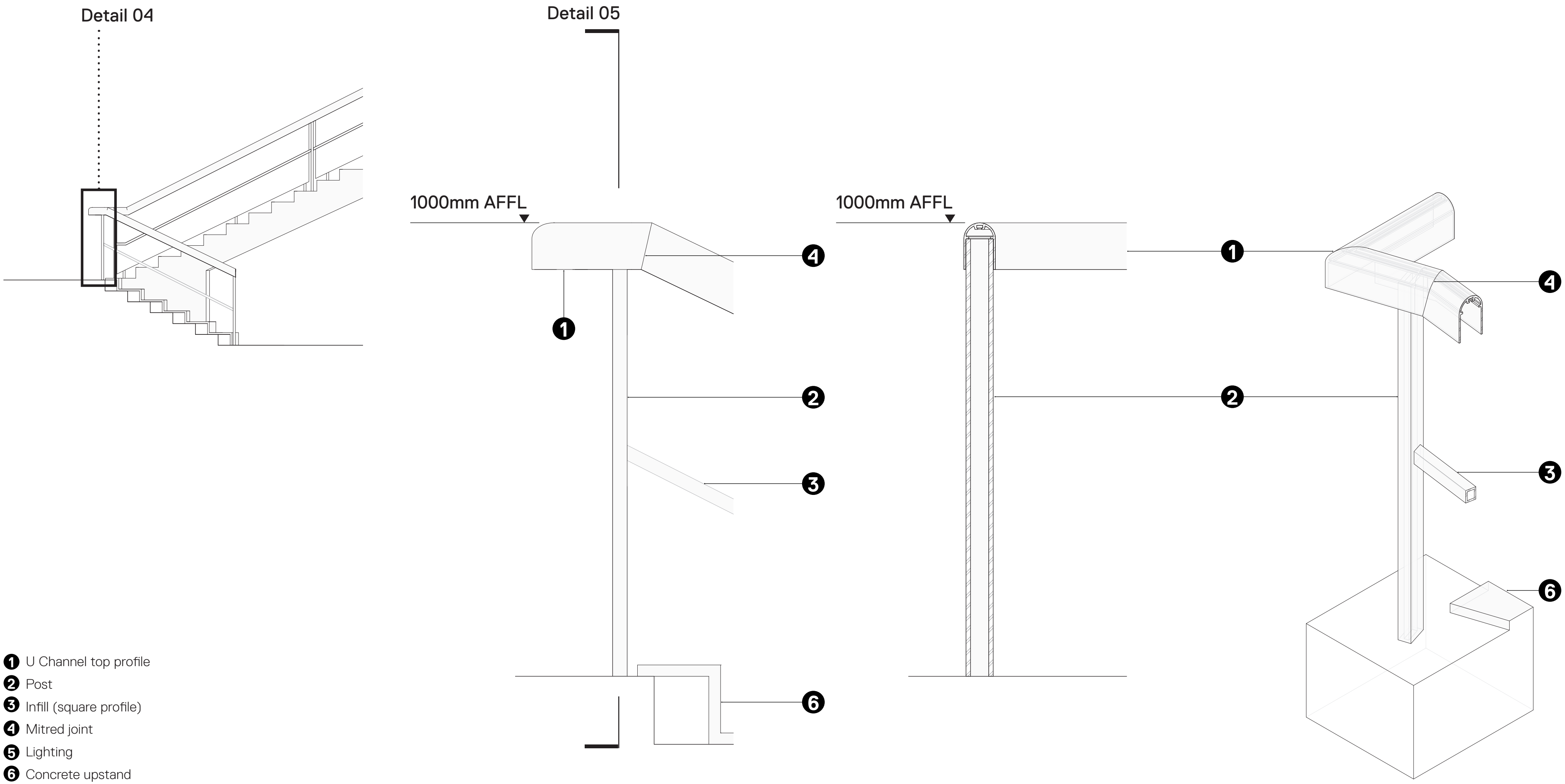
01 02 03

1. U Channel top profile
2. Post
3. Infill (square profile)
4. Mitred joint
5. Fluorescent lighting (“U” channel top profile)
6. Concrete upstand
7. Carpet
8. End cap braced to top profile
9. Base plate below
10. Spigot

01 Handrail partial elevation.
02 Handrail section.
03 Handrail 3D.

Typical details - existing interior

Study 07



04

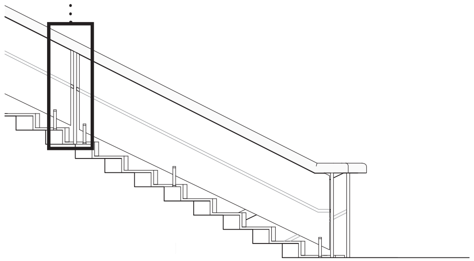
05

06

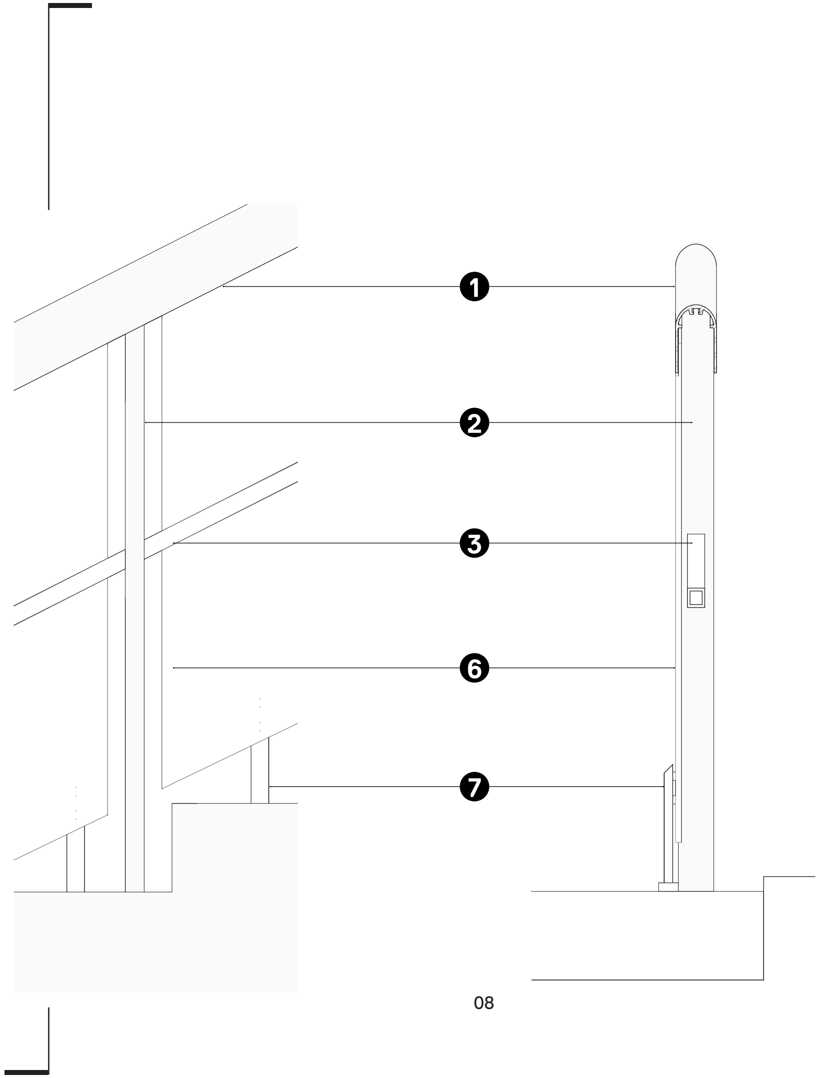
1 U Channel top profile
2 Post
3 Infill (square profile)
4 Mitred joint
5 Lighting
6 Concrete upstand

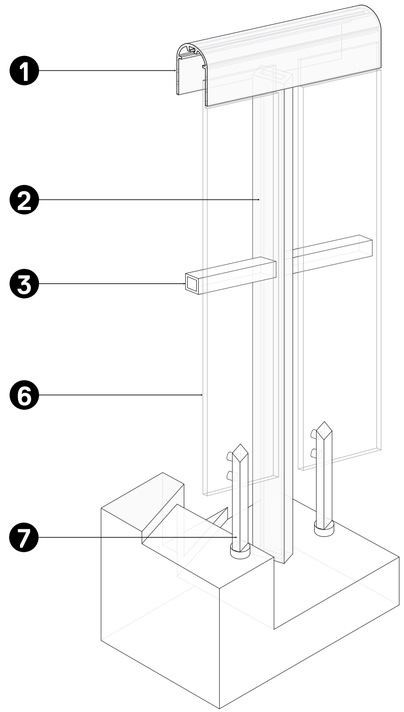
04 Handrail elevation.
05 Handrail section.
06 Handrail 3D.

Detail 07



Detail 08





1 U Channel top profile
2 Post
3 Infill (square profile)
4 Mitred joint
5 Lighting
6 Temporary acrylic infill
7 Acrylic support leg

07 Handrail elevation.
08 Handrail section.
09 Handrail 3D.

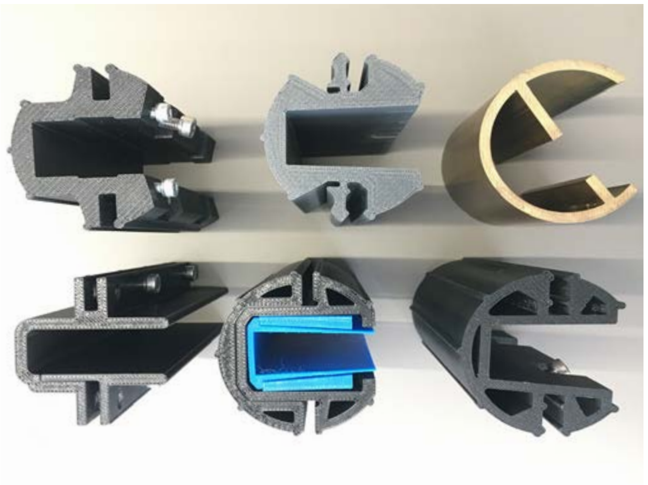
Physical models
Study 08

Model making, prototyping and additive manufacturing techniques were embedded as essential aspects of Grimshaw's iterative design investigation and review process. Evolution of the design process is better served when stakeholders have the opportunity to touch, feel and engage with different materials and surface textures under consideration.

Throughout the design investigation process, a range of different handrail diameter profiles were produced for Opera House oversight and review. Mock-up samples and prototypes were used throughout the design process to allow the design team to visualise regulatory and code requirements and offer alternative solutions through an inclusive prototyping process.

These physical models have also been a valuable tool for the barrier sub-contractors to 'de-risk' the manufacturing and procurement process, as fit and assembly were able to be tested prior to fabrication.

01



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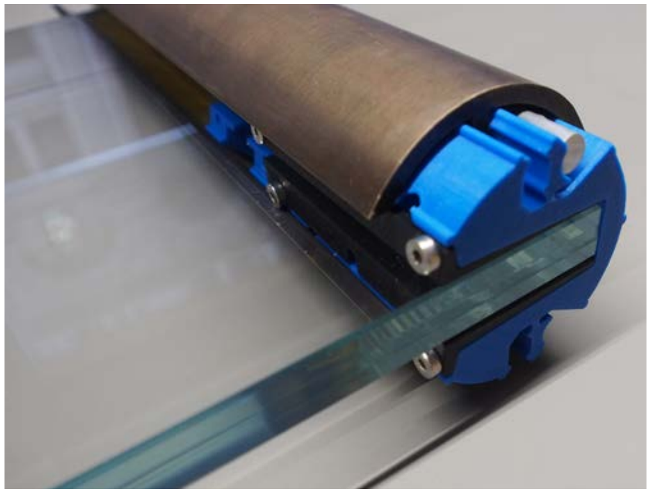


02

01 Wire EDM (electric discharge machining) profile mock-ups.
02 3D Printed mock-up including bronze and glass.
03 3D Printed glazing clamp prototypes.

Chapter 4

Design Criteria & Engineering


OPERA BAR
INDIAN
PARTS & SERVICE

Barriers
Design criteria

The following design criteria were developed in accordance with existing regulatory requirements, Australian standards, alignment with Opera House guiding documents and in consultation with the Opera House EAP.

Barrier infill
- A 125 mm sphere must not be able to pass through any opening. Reference: BCA D2.16, Table D2.16a.

Horizontal wires
- High-tension stainless steel horizontal cables at 60mm to 100mm spacing. Reference: BCA D2.16, Table D2.16b;
- Only permissible where fall is 4m or less. Reference: BCA D2.16, Table D2.16a; and
- Sturdy vertical posts (particularly end posts) required to support tension in cables.

Vertical wires
- High-tension stainless steel near vertical cables at 80mm to 110mm spacing. Reference: BCA D2.16, Table D2.16c; and
- Sturdy horizontal rails required to support tension in cables.

Vertical rods
- Spacing: Max. 125mm; and
- Nom. 15mm rods designed so that they cannot be forced apart enough to allow a 125mm sphere to pass through. Reference: BCA D2.16, Table D2.16a.

Glass
- Nom. 10.76mm clear laminated glass;
- Supported by patch fittings or continuous channels; and
- Any patch fittings located in a climbable zone (150mm to 760mm above FFL) must not be climbable (i.e. less than 10mm projection or 60 degree incline).

Pre-cast concrete / GRC
- Nom. 80mm thick pre-cast concrete to match existing pink granite pre-cast concrete; and
- Any support fixings located in a climbable zone (150mm to 760mm above FFL) must not be climbable (i.e. less than 10mm projection or 60 degree incline).

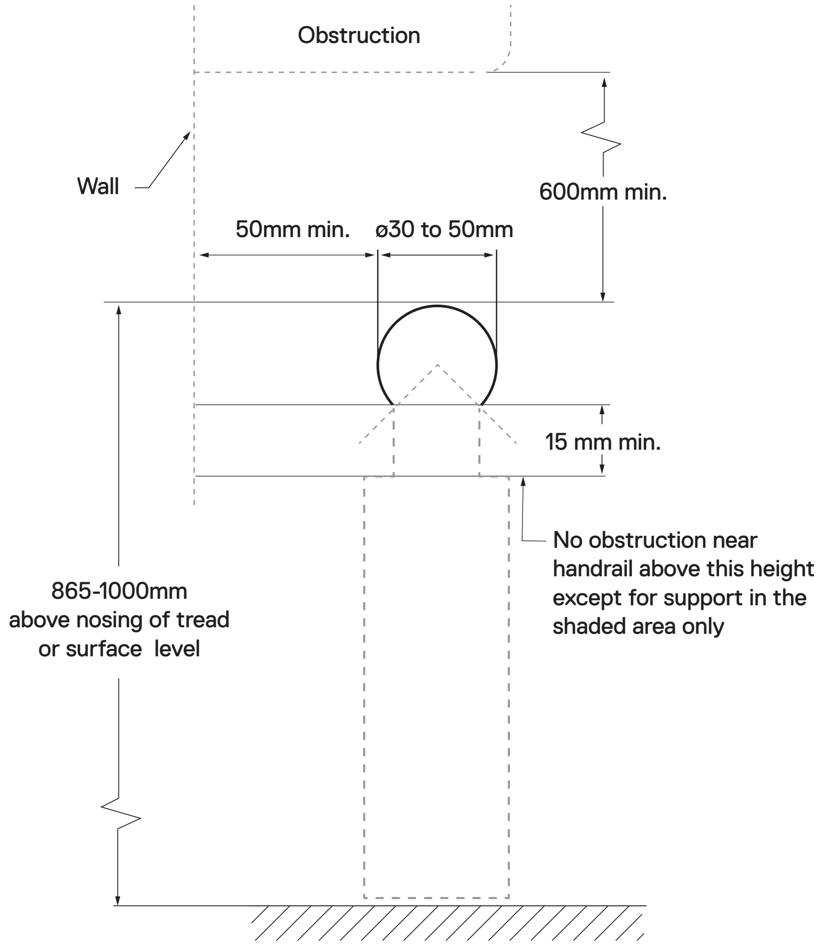
Bronze mesh / perforated sheet
- Nom. 4mm thick brass / bronze perforated sheet or mesh. No holes larger than 13mm within climbable zone. Reference: AS1926.1:2007, Clause 2.3.2;
- To be designed so that it does not permanently deform under load (wind and people); and
- Any support fixings located in a climbable zone (150mm to 760mm above FFL) must not be climbable (i.e. less than 10mm projection or 60 degree incline).

Handrails
Design criteria

Handrails
- Located along at least one side of the ramp or stairs, or both sides where the stairs or ramp are wider than 2m. Reference: BCA D2.17;
- Height: Stairs, landings, walkways etc.: 865mm to 1000mm. Reference: BCA D2.17 & AS1428.1:2009, Clause 12.

Structural design
- No specified loads are nominated within the Standards for handrails (where there is no fall beyond);
- Only a survivability load is necessary to make sure that they handrail does not permanently bend under load;
- Prism propose that a serviceability load of 0.75 kN/m is applied to all handrails (where they are not acting as a barrier, or where there is a separate barrier beyond; and
- Matches the C1/C2 load nominated in AS1170.1 for areas without obstacles for moving people (i.e. stairs, landings etc).

Size & shape
- Circular or elliptical only;
- Diameter: 30mm to 50mm;
- Clearance to wall: min. 50mm; and
- Upper surface to be clear of obstructions or breaks for 270 degrees. Reference: AS1428.1:2009 (See: Illustration 01).



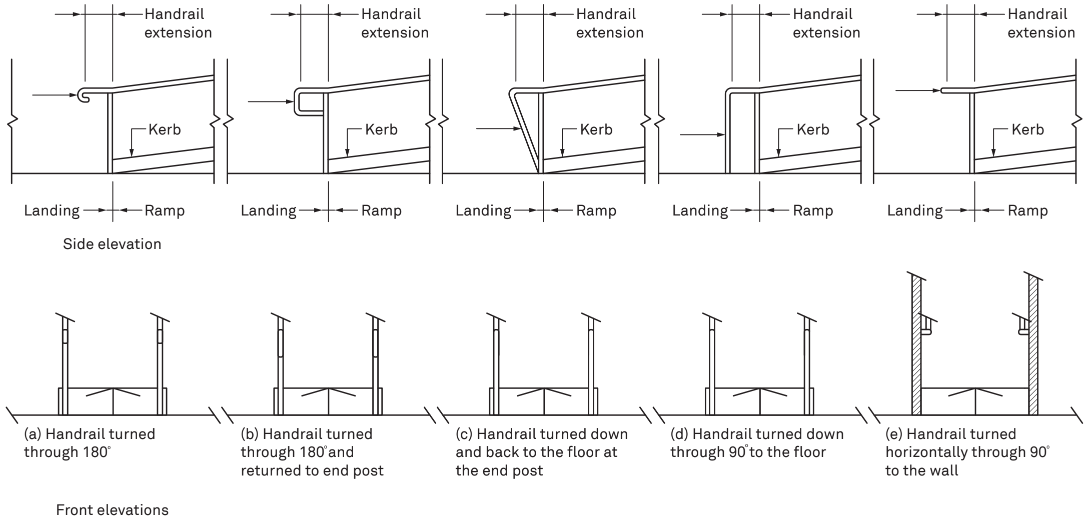
01 Handrail clearance diagram adapted from AS 1428.1-2009.

Length

- Continuous;
- To extent min. 300mm past last stair; and
- End of handrail to turn down 180 degrees, or return to end post or into wall. Reference: AS1428.1:2009 (See: Illustration 02).

Kerbs / kick boards

- A 150mm high kerb or kick board is required to all ramps. Reference: AS1428.1:2009, Clause 10.3; and
- Any support fixings located in climbable zone (150mm to 760mm above FFL) must not be climbable (i.e. less than 10mm projection or 60 degree incline).



02 Ramp and stair handrail terminations (from AS1428:2009)

Bronze handrails
Engineering analysis

The following pages present a summary of the engineering behind the modular handrail design for the Sydney Opera House, as documented by Grimshaw Architects. This analysis extends and details in greater depth that which was presented in the 2009 "Barrier and Handrail Design, Stage 1" Working Group Report by the Sydney Opera House.

Loads

The handrail was analysed under two different conditions:

1. Imposed barrier load C3 - applicable to circulation areas, such as stairs, landings and balconies without fixed seating
2. Imposed barrier load C5 - applicable to areas subject to crowds, wherever the barrier protects from a fall.

Material

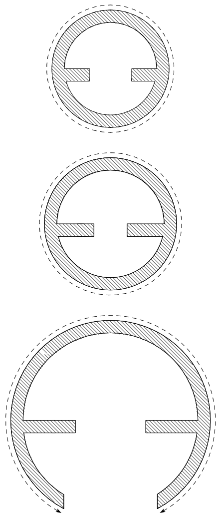
The engineering analysis is based on the mechanical properties of the Austral 412 alloy with the "hard" temper, as provided by Austral.

- Modulus of Elasticity, E = 103GPa
- Shear Modulus, G = 38GPa
- 0.2% Proof Stress, fy = 247MPa

Handrail support

The handrails are connected to the barrier at each end with a pin connection, so the handrails will act as a simply supported beam.

Maximum spans for various internal handrail profiles



Handrail profile	Handrail type	Loading on handrail	Max. span (mm)
47mm Ø - 5mm thick walls	Secondary handrail to meet access requirements. The barrier loading is taken by another bronze element.	0.6kN point load at the centre of span. This is to replicate general serviceability of the secondary handrail with, for example, a person's sitting weight.	2450
53mm Ø - 5mm thick walls	Primary handrail, supporting the imposed barrier loading along the top edge of the barrier.	C5 barrier loading. Refer to AS1170.1 (2002) for all applicable loads.	*1350
80mm Ø - 5mm thick walls	Primary handrail, supporting the imposed barrier loading for both the top edge loads and the infill loads. Note - handrail has aluminium glazing channel insert.	C5 barrier loading. Refer to AS1170.1 (2002) for all applicable loads.	*2450

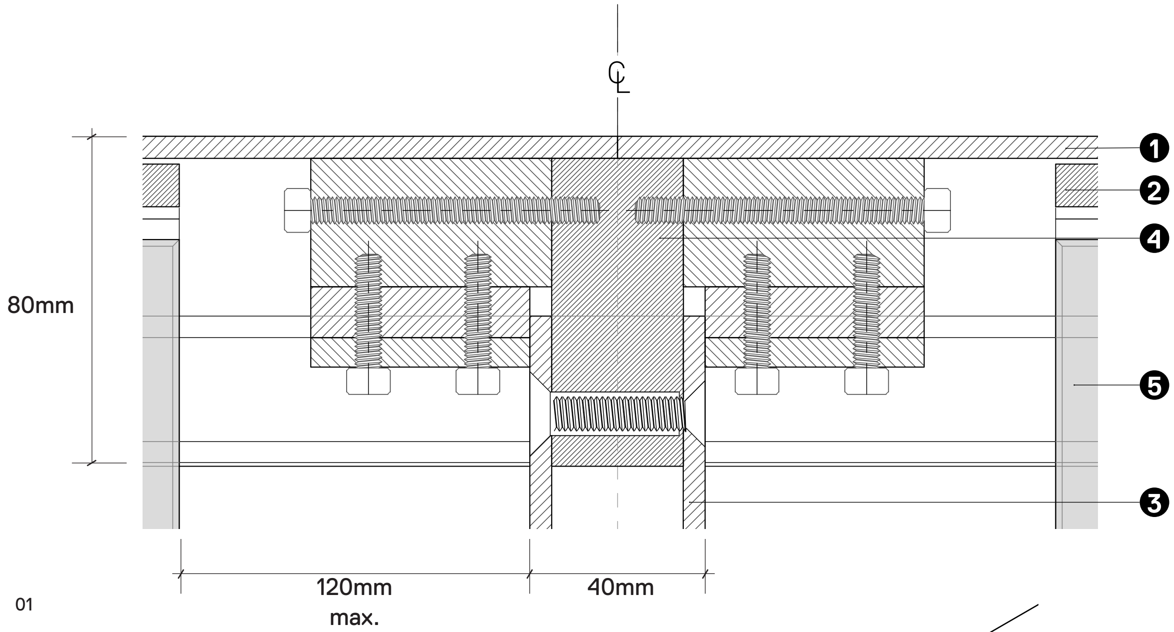
*Subject to confirmation of material properties.

Connections
Engineering analysis

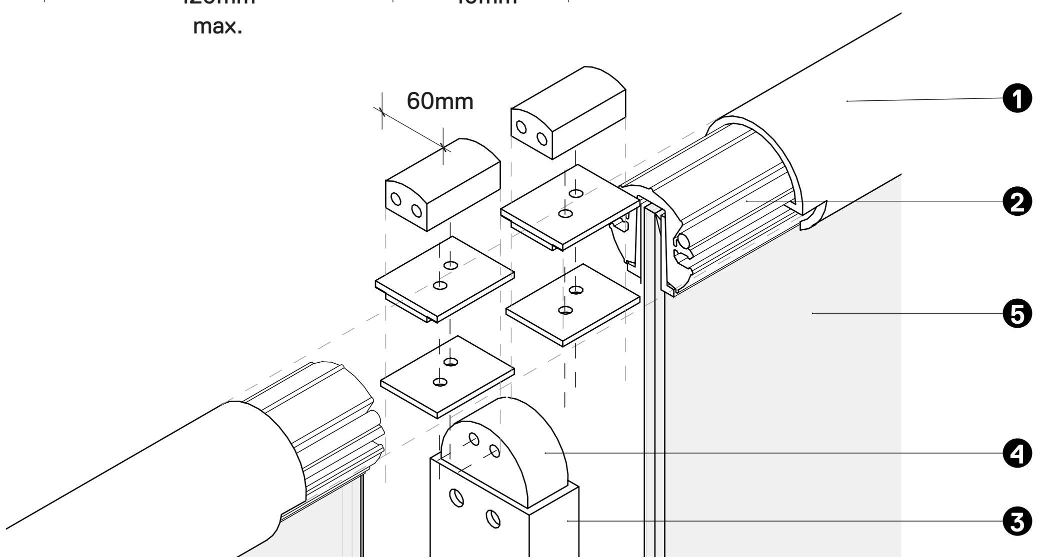
Primary handrail connection to barrier post - 80mm diameter

Diagrams 1 and 2, at right, present differing views of an indicative assembly. The specific connection requirements are illustrated to the right, and the details are summarized below:

- BP 01 - 80mm diameter bronze handrail profile with 5mm thick walls;
- CAS 01 - extruded aluminium clamp to suspend glazed infill panel, cap screw fixing beyond;
- PP 01 - 80mm x 40mm bronze post with 5mm thick walls;
- PP 04 - architectural bronze post profile covers connection between BP 01 profiles; and
- GLA - low iron glazed infill panel with polished bevel edges.



01



02

❶ BP 01 - Barrier Profile 80mm dia.
❷ CAS 01 - Cassette extrusion
❸ PP 01 - Post Profile 80 x 40mm
❹ PP 04 - Post Profile, splice connection
❺ GLA - Glass infill panel

01 Assembly section.
02 Assembly isometric.

Connections
Engineering analysis

Primary handrail connection to barrier - 53mm diameter

Two fixing arrangements are proposed for the 53mm diameter handrail profile:

1. HN 06 - Expressed spigot connection (Illustration 01), and;
2. HN 07 - Concealed spigot connection (Illustration 02).

The following minimum dimensions and sizes are required:

- FX 01 - All fixings are M8 stainless steel A4-70 bolt fixings. Hex head, countersunk or other head types are acceptable;

HN 06 - Concealed connection
Architectural bronze extrusion

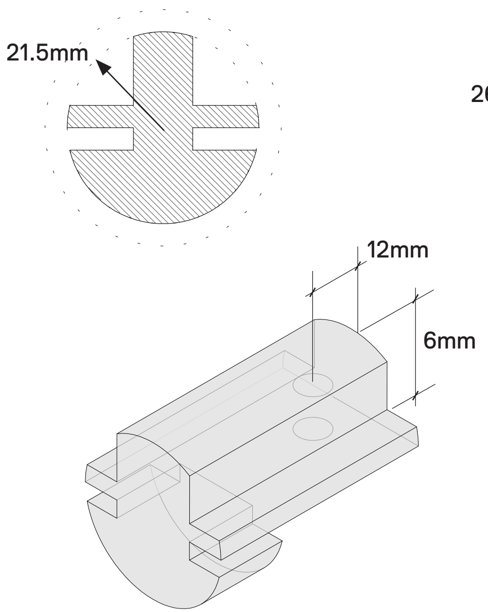
Application
- Free-standing handrail (C5 loading)

Extrusion properties
- Material;
- Fixings; and
- Tolerances

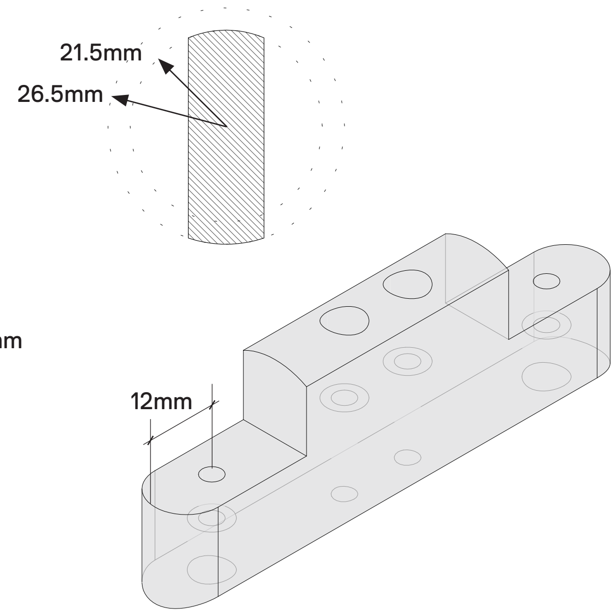
HN 07 - Concealed connection
Architectural bronze extrusion

Application
- Free-standing handrail (C5 loading)

Extrusion properties
- Material;
- Fixings; and
- Tolerances



01



02

01 HN 06 - Concealed spigot connection.
02 HN 07 - Concealed spigot connection.

Connections
Engineering analysis

Secondary handrail connection to outrigger - 47mm diameter

The secondary handrails are fixed to outriggers off the barrier post in the following arrangement:

1. HN 02 - Concealed spigot connection (Illustration 03).

2. HN 03 - Concealed spigot connection (Illustration 04)

The following minimum dimensions and sizes are required:

- FX 01 - All fixings are M6 stainless steel A4-70 bolt fixings. Hex head, countersunk or other head types are acceptable.

HN 02 - Concealed connection
Architectural bronze - machined from extrusion

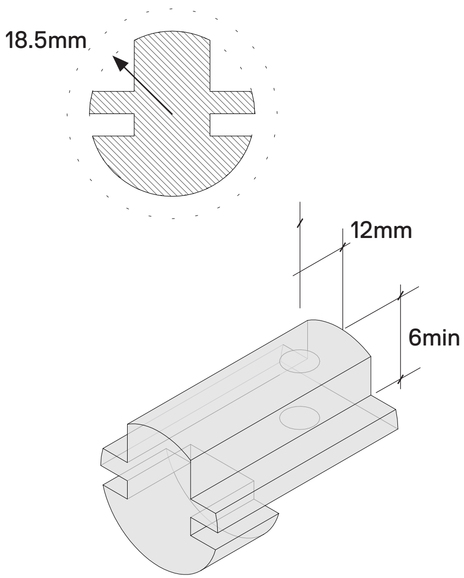
Applications
- Wall mounted handrail; and
- Handrail (C3 loading).

Extrusion properties
- Material;
- Fixings; and
- Tolerances.

HN 03 - Concealed connection
Architectural bronze - machined from extrusion

Applications
- Wall mounted handrail; and
- Handrail (C3 loading).

Extrusion properties
- Material;
- Fixings; and
- Tolerances.



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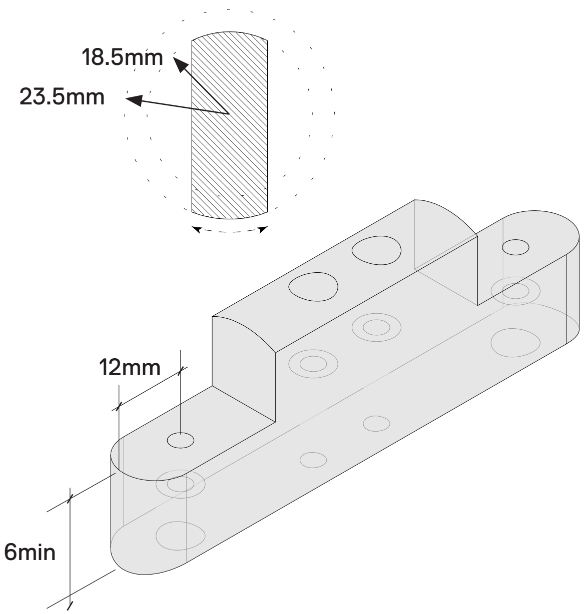


04

03 HN 02 - Concealed spigot connection.
04 HN 03 - Concealed spigot connection.

Connections
Engineering analysis

Expressed handrail connections 56mm and 47mm diameter

The secondary handrails are fixed to outriggers off the barrier post in the following arrangement:

1. HN 01 - Expressed connection 47mm (Illustration 01).

2. HN 05 - Expressed connection 53mm (Illustration 02).

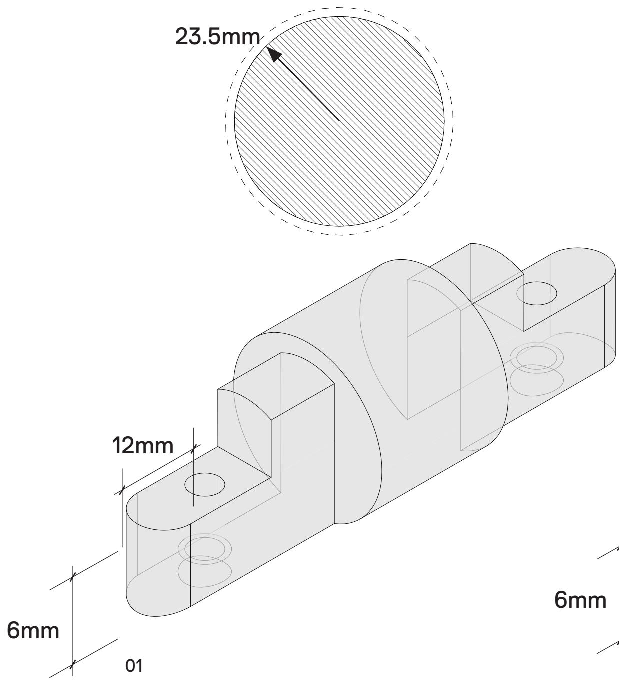
The following minimum dimensions and sizes are required:

- FX 01 - All fixings are M6 stainless steel A4-70 bolt fixings. Hex head, countersunk or other head types are acceptable.

HN 01 - Expressed connection
Architectural bronze - machined from solid extrusion

Applications
- Wall mounted handrail; and
- Handrail (C3 loading).

Extrusion properties
- Material;
- Fixings; and
- Tolerances.

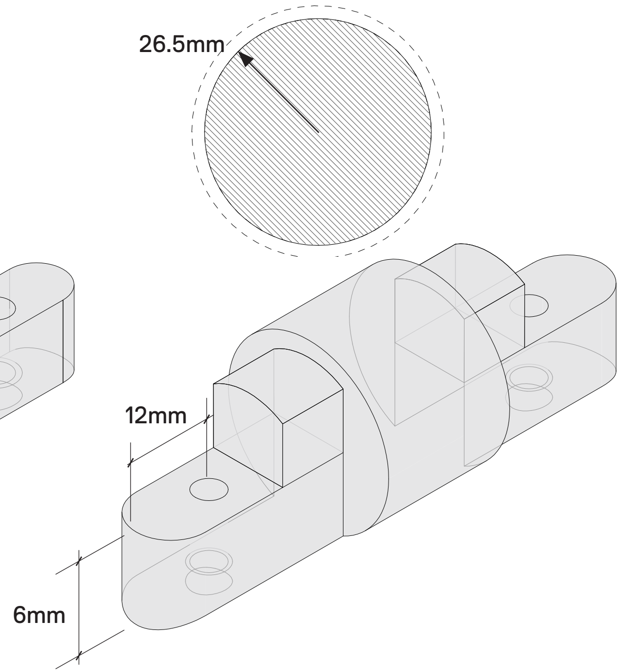


01

HN 05 - Expressed connection
Architectural bronze extrusion

Application
- Freestanding handrail (C5 loading)

Extrusion properties
- Material;
- Fixings; and
- Tolerances



02

01 HN 01 - Expressed connection.
01 HN 05 - Expressed connection.

Bronze barriers
Engineering analysis

Minimum requirements for the bronze barriers in different load conditions

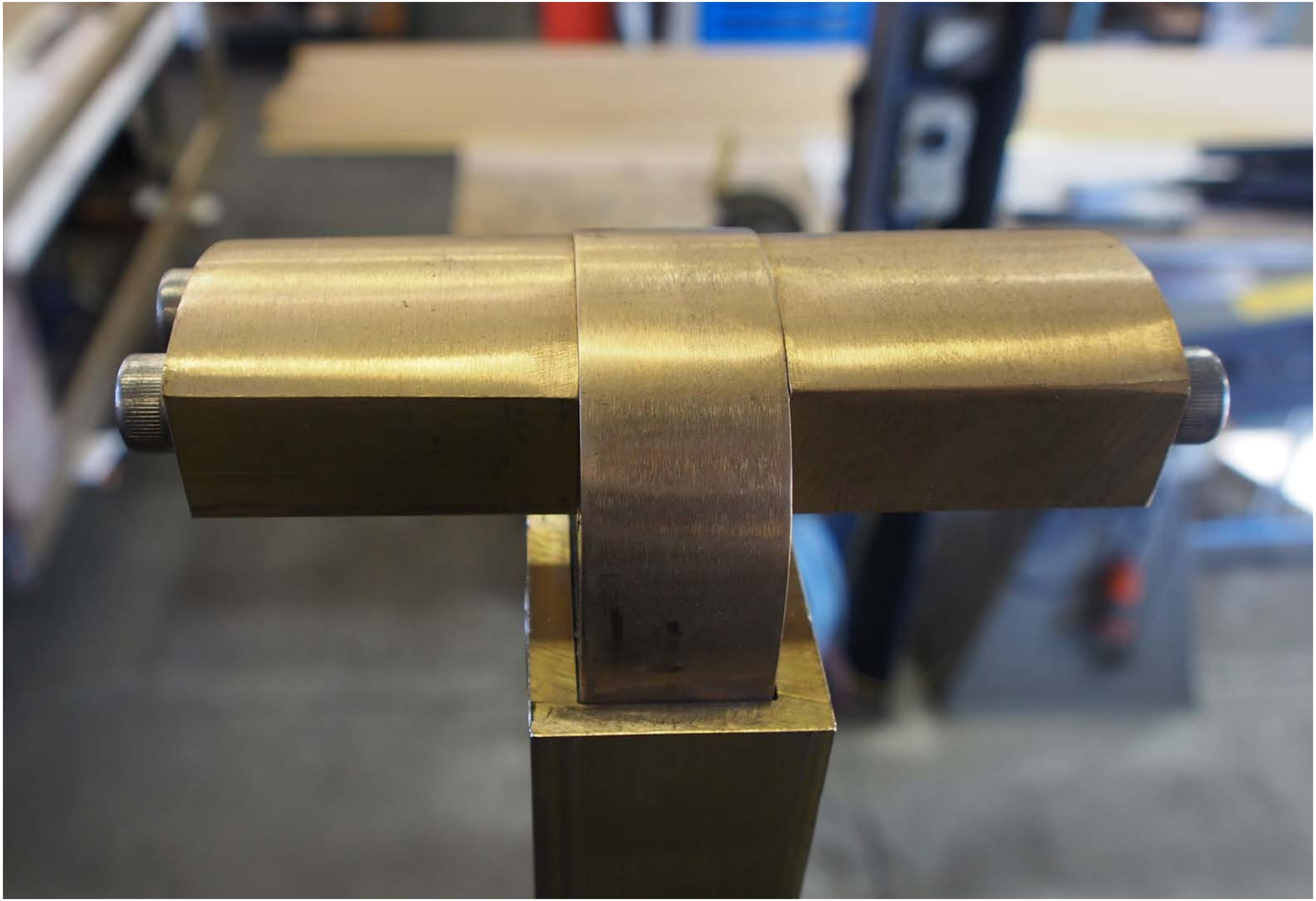
System Code	Span (mm)	Height (mm)	Handrail support mode	Barrier type	C3 loading - post requirements	C5 loading - post requirements
BAR 100	2400	1100 (internal)	Simply supported	Cantilevered glass from the top handrail. The glass is not fixed to the post at any point. Note - deflection limit = Height/60	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 100 mm minimum	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 230 mm minimum
Not used.	2400	1100 (internal)	Simply supported	Three-side supported glass, with the post supporting the side edges of the glass. Note - deflection limit = Height/125	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 100 mm minimum	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 470 mm minimum Note: the spigot is unable to be bronze alloy Austral 412 in this instance. Prism Facades recommend a steel spigot to meet deflection requirements.
BAR 200	2400	1200 (external)	Simply supported	Vertical tensioned rods Note - deflection limit = Height/60	N/A There are no locations where an exterior barrier would be designed to C3 loading	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 430mm minimum Note: the spigot is unable to be bronze alloy Austral 412 in this instance. Prism Facades recommend a steel spigot to meet deflection requirements.
BAR 300	1350	1000 (internal)	Simply supported	Three-side supported glass, with the post supporting the side edges of the glass. Note - deflection limit = Height/125	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 100 mm minimum	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 290 mm minimum
Not used.	900	1000 (internal)	Simply sup-ported	Three-side supported glass, with the post supporting the side edges of the glass. Note - deflection limit = Height/125	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 100 mm minimum	For an 80x40 post with a 5mm wall thickness, the connection spigot at the base is required to have a height, x of: x = 140 mm minimum

Member sizes
Engineering analysis

The C5 crowd load is the highest structural load that the Opera House barriers must be able to resist for a building of its type. Studies were conducted in order to investigate how different post modules would impact member sizes, with closer post centres having an overall effect of reducing element sizes. The following table details the resulting member sizes for investigations carried out in the Eastern and Northern Foyers.

Member sizes

	C3 Crowd load		C5 Crowd load		
	1000mm tall post spacing		Eastern Foyer post spacing		All other interior barriers
	900	2400	1200	1350	2400
Post	60x25mm hollow - 5mm wall	80x40mm hollow - 10mm wall	80x40mm hollow - 12mm wall	80x40mm hollow - 15mm wall	80x40mm hollow - 15mm wall
Top rail	N/A	N/A	N/A	N/A	N/A
Hand rail	Ø38	Ø47	Ø38	Ø53	Ø47
Lighting	✓	✓	✓	✓	✓
Glass thickness (mm)	10.76	10.76	15.00	15.00	17.76



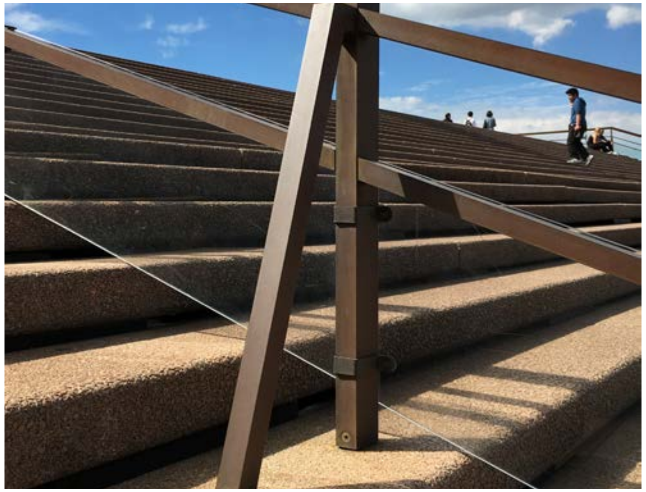
Chapter 5

Existing Conditions

5.1

Exterior Conditions & Optioning

01



03

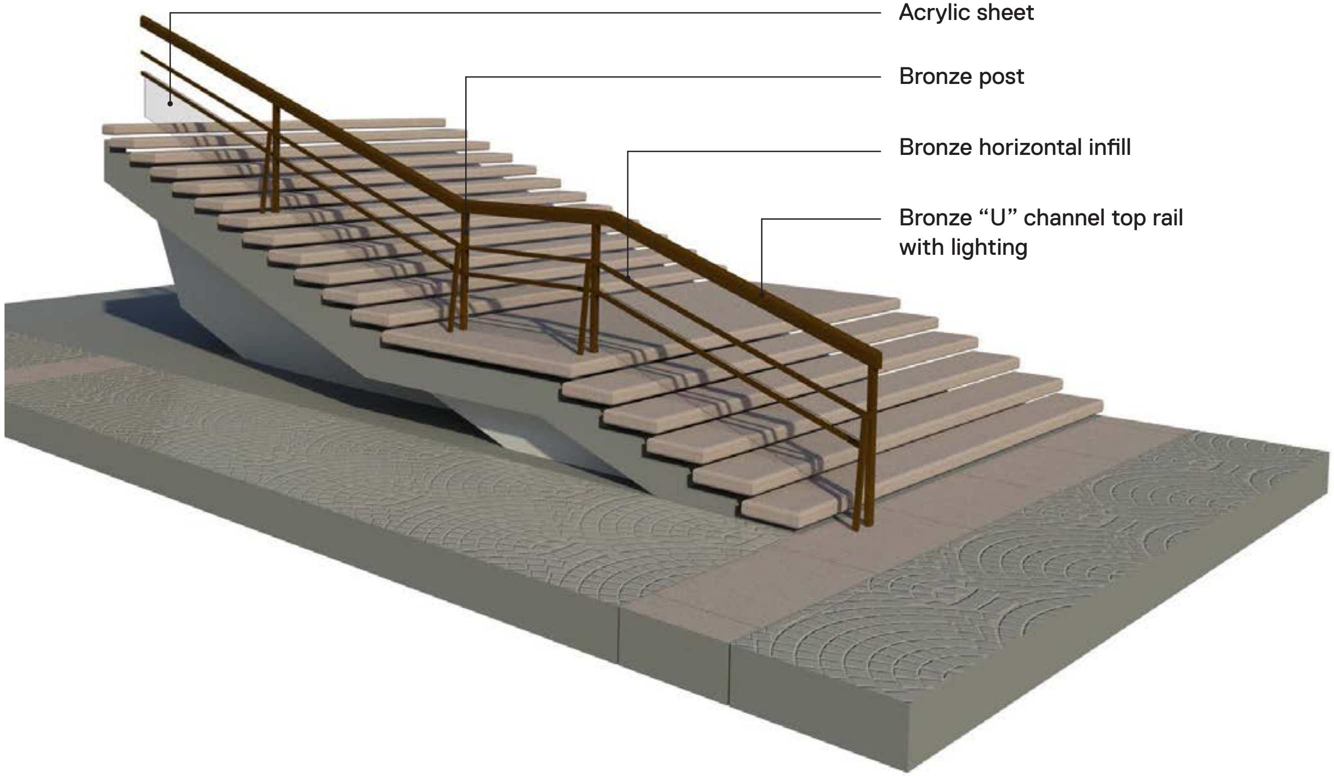
02

01 Podium handrail.
02 Top view.
03 Acrylic and infill bars detail.

External condition
Existing

Handrail Height: 1000mm
Barrier Height: 1000mm

Currently the main podium stair has a handrail with two horizontal infill bars which are viewed as climbable elements. A acrylic sheet has been introduced at low level to fill the lowest section on this rail. The 2014 Handrail and Balustrade Masterplan deemed this not in code compliance and not fit-for-purpose in terms of aesthetics. Currently the rail has a concealed fluorescent light, which requires daily inspection and regular electrical maintenance.



Vertical rod infill
Preferred option

Handrail Height: 900mm
Barrier Height: 1200mm
Integrated handrail and top rail lighting
C5 Crowd loading

The base system, comprising a bronze post, a dominant top rail and an integrated handrail that could be adapted to accommodate various transitions and termination options emerged as the heritage and engineering considerations were evaluated. The 80mm circular toprail affords greater spans that match the existing building grid.

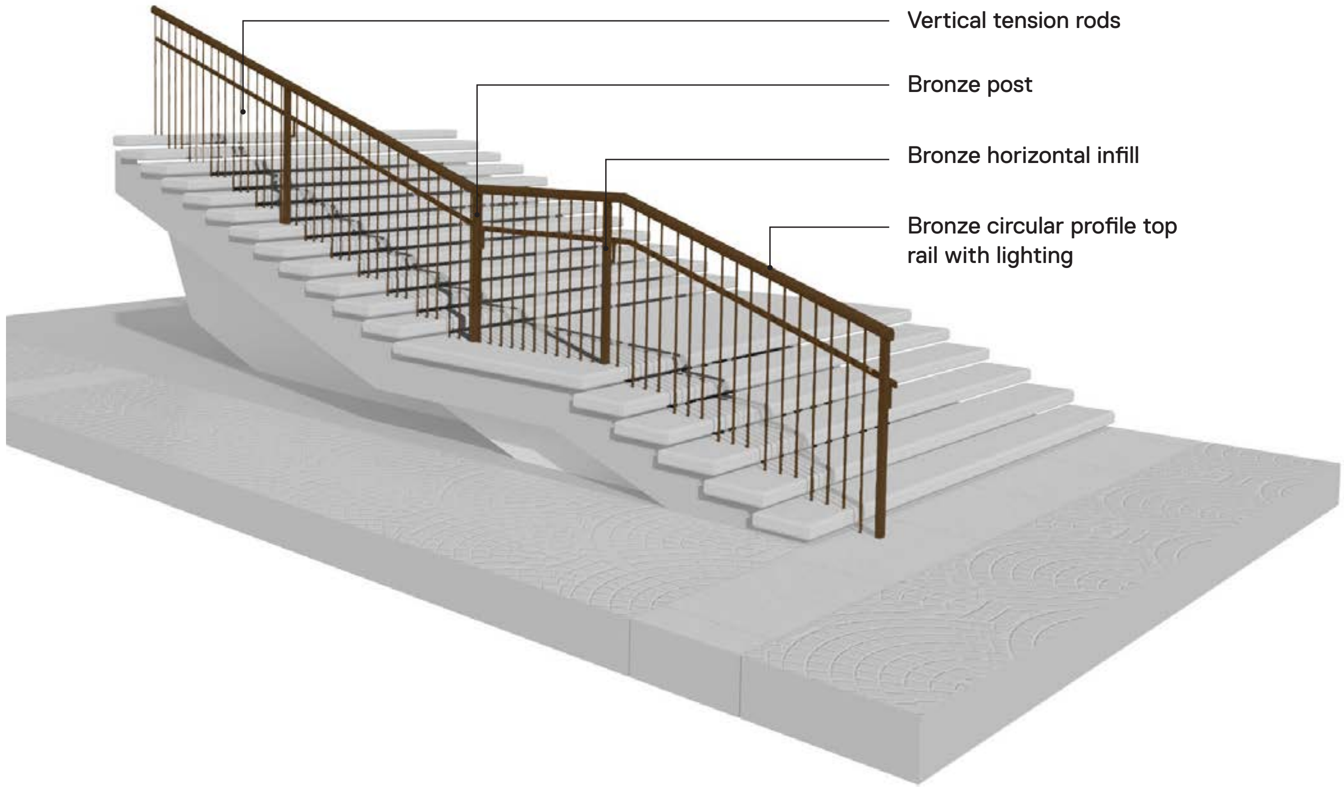
A preferred infill option selected by the EAP and Conservation Council representatives uses vertical tension rods anchored to the pre-cast granite setts and stair treads to tensioning devices concealed within the top rail.

Pros

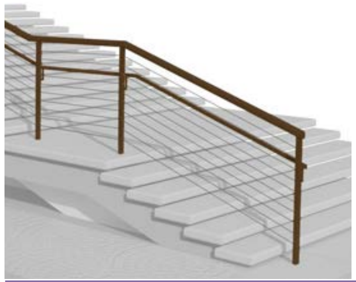
- Top rail carries no additional load;
- No visible fixings; and
- Considered non-climbable.

Cons

- Visually obtrusive - rods at 100mm spacing;
- Infill is modular in nature, however site conditions vary;
- Resulting in uneven spacing between rods; and
- Requires new fixing points for each vertical rod.



External condition
Comparative options - bars, rods & glass infill

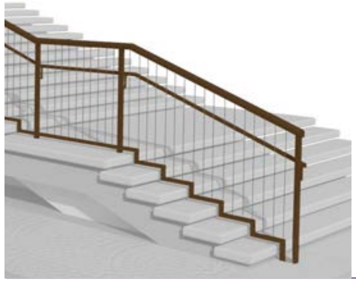
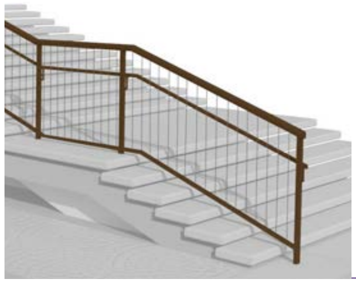
Visualisation	Infill type	Heights	Pros	Cons	Notes
	**Vertical bars**	Handrail: 900mm Barrier: 1200mm	• Top rail carries no additional load; • No visible fixings; and • Considered non-climbable.	• Visually obtrusive - rods at 100mm spacing; • Infill is modular in nature, however site conditions vary; • Resulting in uneven spacing between rods; and • Requires new fixing points for each vertical rod.	Size of rods rigid enough to resist infill loads is visually prominent, investigate material options to allow aging and to reduce rod diameter.
	**Horizontal rods**	Handrail: 900mm Barrier: 1200mm	• Top rail carries no additional load; • No visible fixings; and • Considered climbable.	• Visually translucent - rods at 100mm spacing; • Infill is modular in nature, however changes in plan result in compromised details as the tension rods connect to the post at an acute angle.	Similar to the Western Concourse, however excluded due to climbable in areas where falls are greater than 4m.
	**Glass**	Handrail: 900mm Barrier: 1200mm	• Visual transparency in natural light conditions; • No visible fixings; • Uses existing fixing points; • Non-modular, therefore adaptable to varying conditions; and • Considered non-climbable.	• Rail has gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry; • Potential 'light wash' from integrated lighting; and • Additional weight and therefore load on existing fixings.	Use of glass on exterior barriers was previously ruled out in 2008 and was again confirmed by the Eminent Architects Panel.

External condition
Comparative options - glass infill

Visualisation	Infill type	Heights	Pros	Cons	Notes
	**Glass**	Handrail: 900mm Barrier: 1200mm	• Visual transparency under natural light; • Non-modular, therefore adaptable to varying conditions; • The impact of the additional weight of the infill is minimised by using mid-supports; and • Considered non-climbable.	• Rail has gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry; and • Potential 'light wash' from integrated lighting.	Use of glass on exterior barriers was previously ruled out in 2008 and was again confirmed by the EAP
	**Glass**	Handrail: 900mm Barrier: 1200mm	• Visual transparency under natural light; • No visible fixings; • Non-modular, therefore adaptable to varying conditions; • Infill responds to existing stair geometry; • Uses existing fixing points; and • Considered non-climbable.	• Potential 'light wash' from integrated lighting; and • Additional weight and therefore load on existing fixings.	Base fixing channel considered unsightly, use of glass on exterior barriers was previously ruled out in 2008 and was again confirmed by the EAP
	**Glass**	Handrail: 900mm Barrier: 1200mm	• Visual transparency under natural light; • No visible fixings; • Non-modular, therefore able to adapt to varying conditions; • Infill responds to existing stair geometry; • Uses existing fixing points; and • Considered non-climbable.	• Potential 'light wash' from integrated lighting; and • Additional weight and therefore load on existing fixings.	Closure of the stair openings considered unsightly, use of glass on exterior barriers was previously ruled out in 2008 and was again confirmed by the EAP

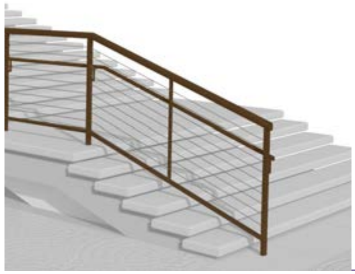
External condition

Comparative options - vertical cable infill

Visualisation	Infill type	Heights	Pros	Cons	Notes
	**Vertical cable**	Handrail: 900mm Barrier: 1200mm	• Visual transparency both in the day and at night; • Light weight in nature; • Uses existing fixing points; and • Considered non-climbable.	• Either large top or bottom rail required to conceal tensioner; and • Infill is modular in nature, however site conditions vary resulting in uneven spacing between cables.	Continuous bottom rail considered unsightly.
	**Vertical cable**	Handrail: 900mm Barrier: 1200mm	• Visual transparency both in the day and at night; • Light weight in nature; • Uses existing fixing points; and • Considered non-climbable.	• Rail gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry; • Either large top or bottom rail required to conceal tensioner; and • Infill is modular in nature, however site conditions vary resulting in uneven spacing between cables.	Continuous bottom rail considered unsightly.
	**Vertical cable**	Handrail: 900mm Barrier: 1200mm	• Visual transparency both in the day and at night; • Light weight in nature; • Uses existing fixing points; and • Considered non-climbable.	• Rail has gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry; • Either large top or bottom rail required to conceal tensioner; and • Infill is modular in nature, however site conditions vary resulting in uneven spacing between cables.	Continuous bottom rail considered unsightly including use of central post to resist tension loads. Investigate use of mounting cartridge in top rail to stiffen in lieu of the central post.

External condition

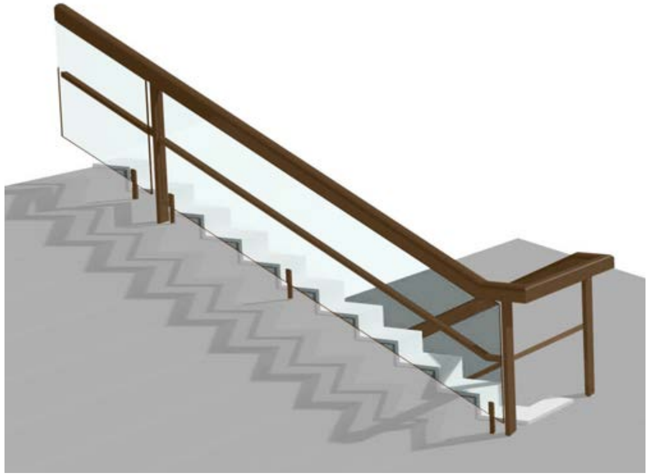
Comparative options - horizontal cable infill

Visualisation	Infill type	Heights	Pros	Cons	Notes
	**Horizontal cable**	Handrail: 900mm Barrier: 1200mm	• Visual transparency both in the day and at night; • Light weight in nature; • Top rail carries no additional load; • Uses existing fixing points; and • Is non-modular and is therefore able to adapt to varying conditions.	• Considered climbable; and • Rail has gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry.	Continuous bottom rail considered unsightly including use of central post to resist tension loads. Investigate use of mounting cartridge in top rail to stiffen in lieu of the central post.
	**Horizontal cable**	Handrail: 900mm Barrier: 1200mm	• Visual transparency both in the day and at night; • Light weight in nature; • Top rail carries no additional load; • Uses existing fixing points; and • Is non-modular and is therefore able to adapt to varying conditions.	• Considered climbable; and • Rail has gaps of up to 140mm between the infill panel and the glazing at the start of each riser due to existing stair geometry.	Similar to the Western Concourse, however excluded due to climbable in areas where falls are greater than 4m.

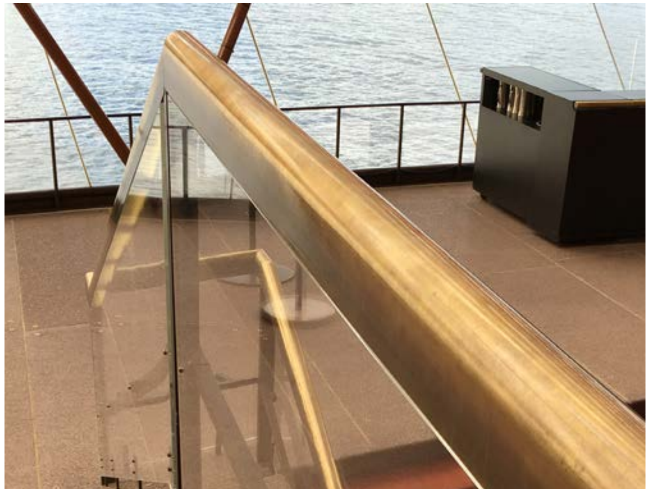
5.2

Interior Conditions & Optioning

01



03



02

01 Existing Northern Foyer handrail.
02 Existing Northern Foyer handrail.
03 Existing Internal handrail render.

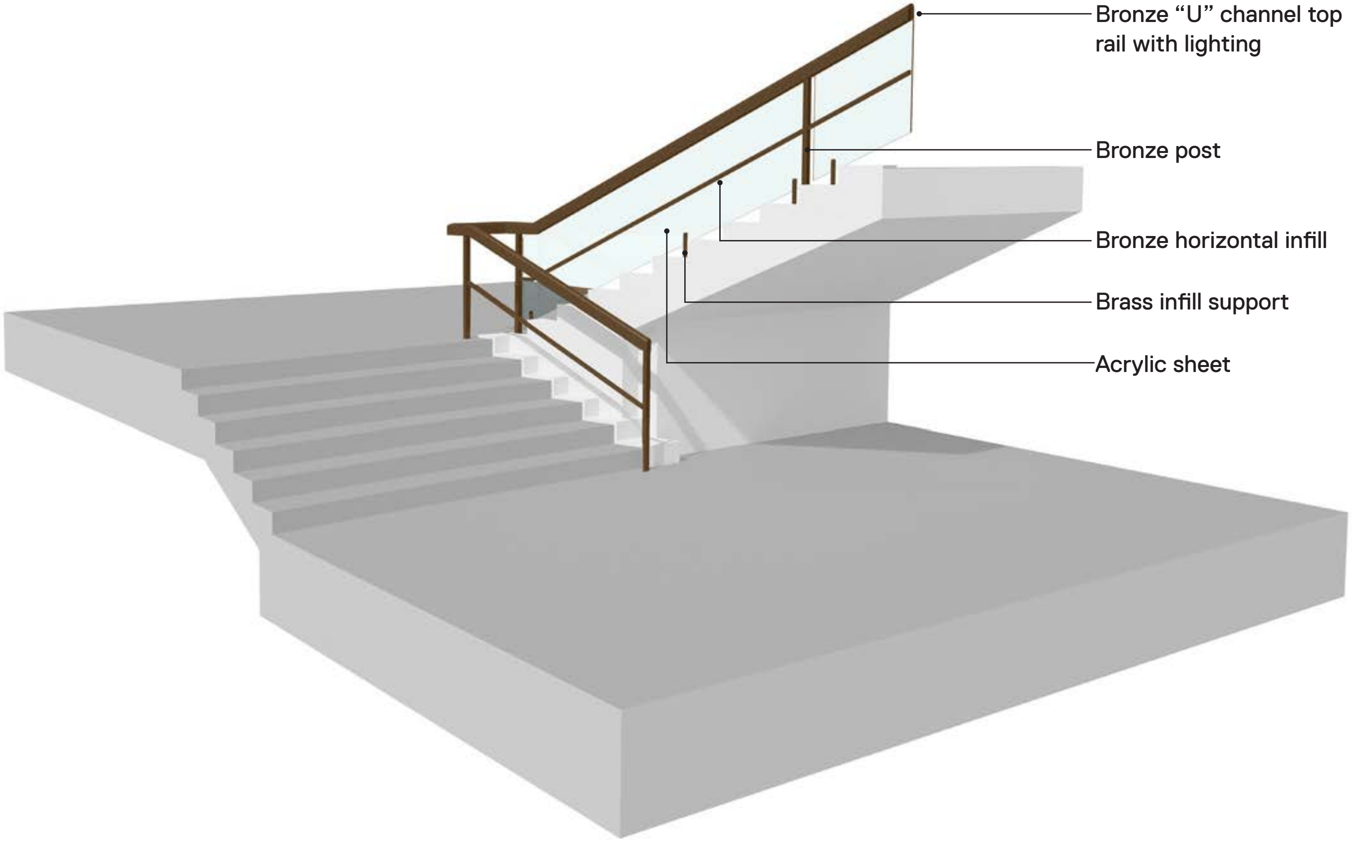
Internal condition
Existing

Handrail Height: 1000mm
Barrier Height: 1000mm

Currently the main Northern Foyer and interior stairs have a handrail with one horizontal infill bars which is viewed as a climbable element. An acrylic sheet has been introduced at to mitigate climbing of the mid rail.

The 2014 Handrail and Balustrade Masterplan deemed this not in code compliance and the inclusion of the acrylic infill not fit for purpose in terms of aesthetics.

Currently the rail has a T5 fluorescent light concealed within the U-channel top rail, which requires daily inspection and regular electrical maintenance.



Internal glass infill

Preferred option

Handrail Height: 900mm
Barrier Height: 1100mm
Integrated handrail lighting
C5 Crowd loading

The base system, comprising a bronze post, a dominant top rail, a lower rail, and an integrated handrail that could be adapted to accommodate various transitions and termination options, emerged as the heritage and engineering considerations were evaluated. The 80mm toprail affords greater spans that match the existing building grid.

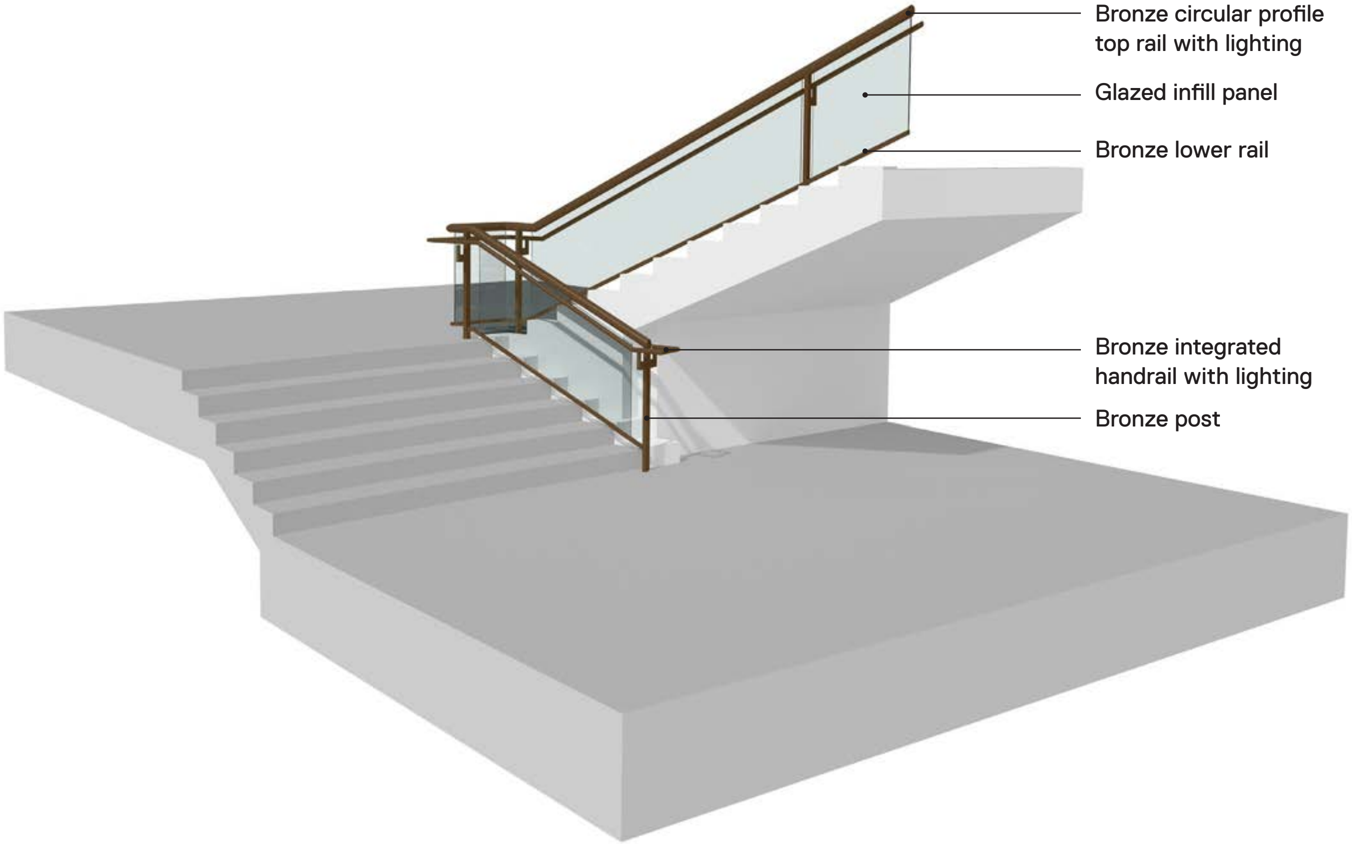
A preferred infill option selected by the EAP and Conservation Council representatives uses a floating plane of glass supported by the 80mm top rail with minimal hardware allowing it to be suspended above the precast granite setts and stair treads.

Pros

- Visual transparency both in the day and at night;
- Uses existing fixing points; and
- Is non-modular and is therefore able to adapt to varying conditions.

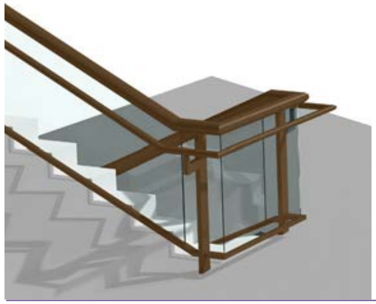
Cons

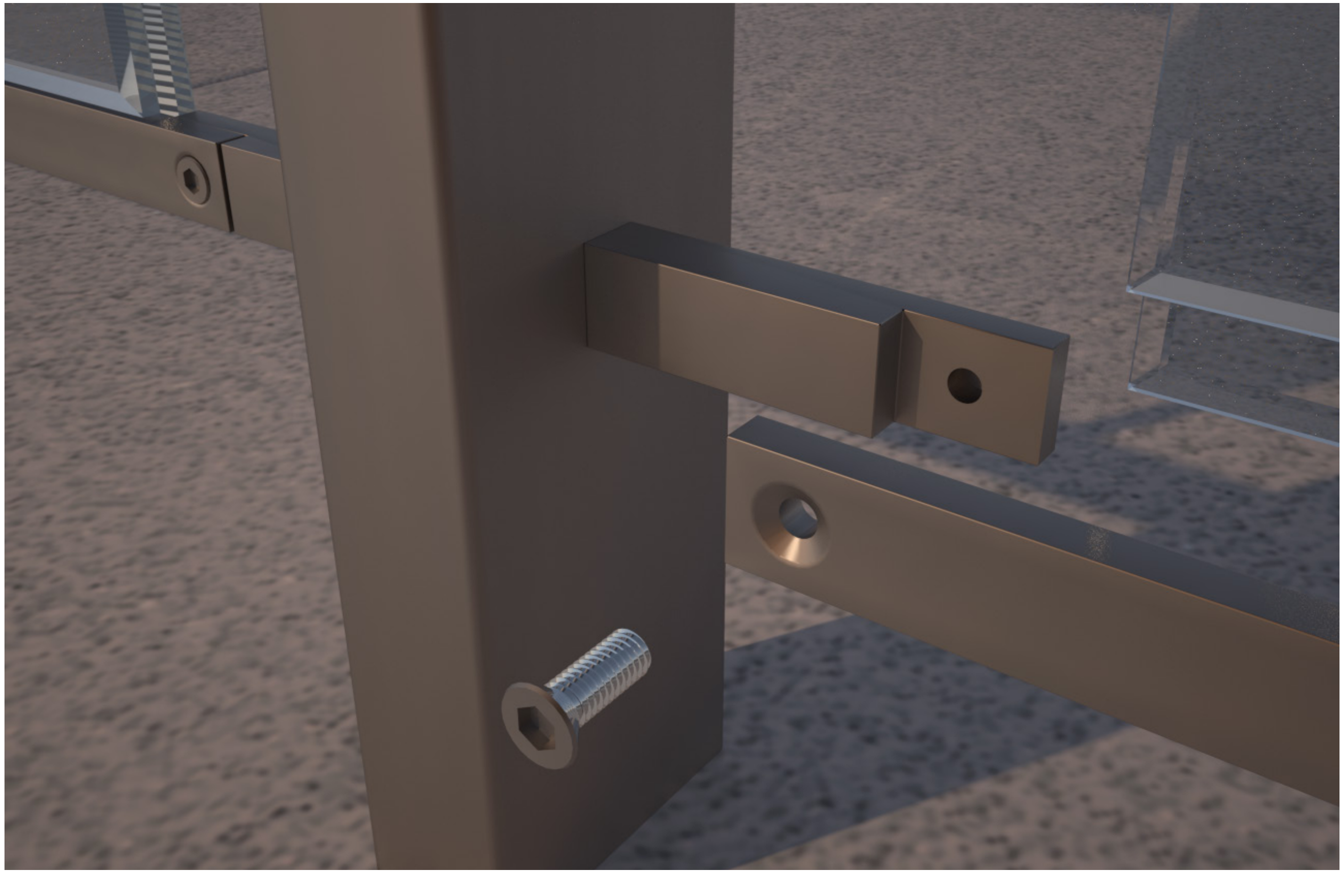
- Requires lower rail;
- Glass failure (mittigated through use of laminated glass) ; and
- Potential light wash and reflectivity.



Internal condition

Comparative options

Visualisation	Infill type	Heights	Pros	Cons	Notes
	**Internal glass**	Handrail: 900mm Barrier: 1000mm	• Visual transparency both in the day and at night; • Suspended glass infill with no visible fixings; • Uses existing fixing points; and • Non-modular and is therefore able to adapt to varying conditions.	• Glass failure; (mitigated through use of laminated glass) and • Potential light wash and reflectivity.	Lower rail has been reduced to 25mm high and integrated into the glazing assembly.
	**Internal glass**	Handrail: 900mm Barrier: 1000mm	• Visual transparency both in the day and at night; • Suspended glass infill with no visible fixings; • Uses existing fixing points; and • Non-modular and is therefore able to adapt to varying conditions.	• Glass failure; (mitigated through use of laminated glass) and • Potential light wash and reflectivity.	Considered overly complex with the addition of handrail and mid rail.
	**Internal glass**	Handrail: 900mm Barrier: 1000mm	• Visual transparency both in the day and at night; • Suspended glass infill with no visible fixings; • Uses existing fixing points; and • Is non-modular and is therefore able to adapt to varying conditions.	• Glass failure; (mitigated through use of laminated glass) and • Potential light wash and reflectivity.	While this option was initially preferred, it did not satisfy the testing requirements. It may be achievable in the future, with an alternate fixing detail within the top rail.



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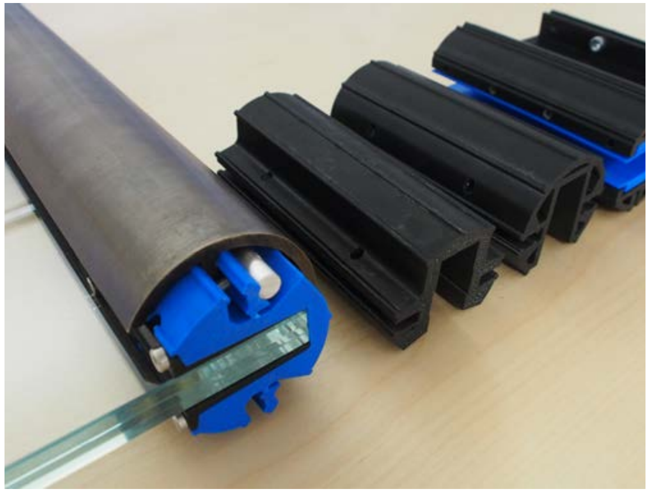
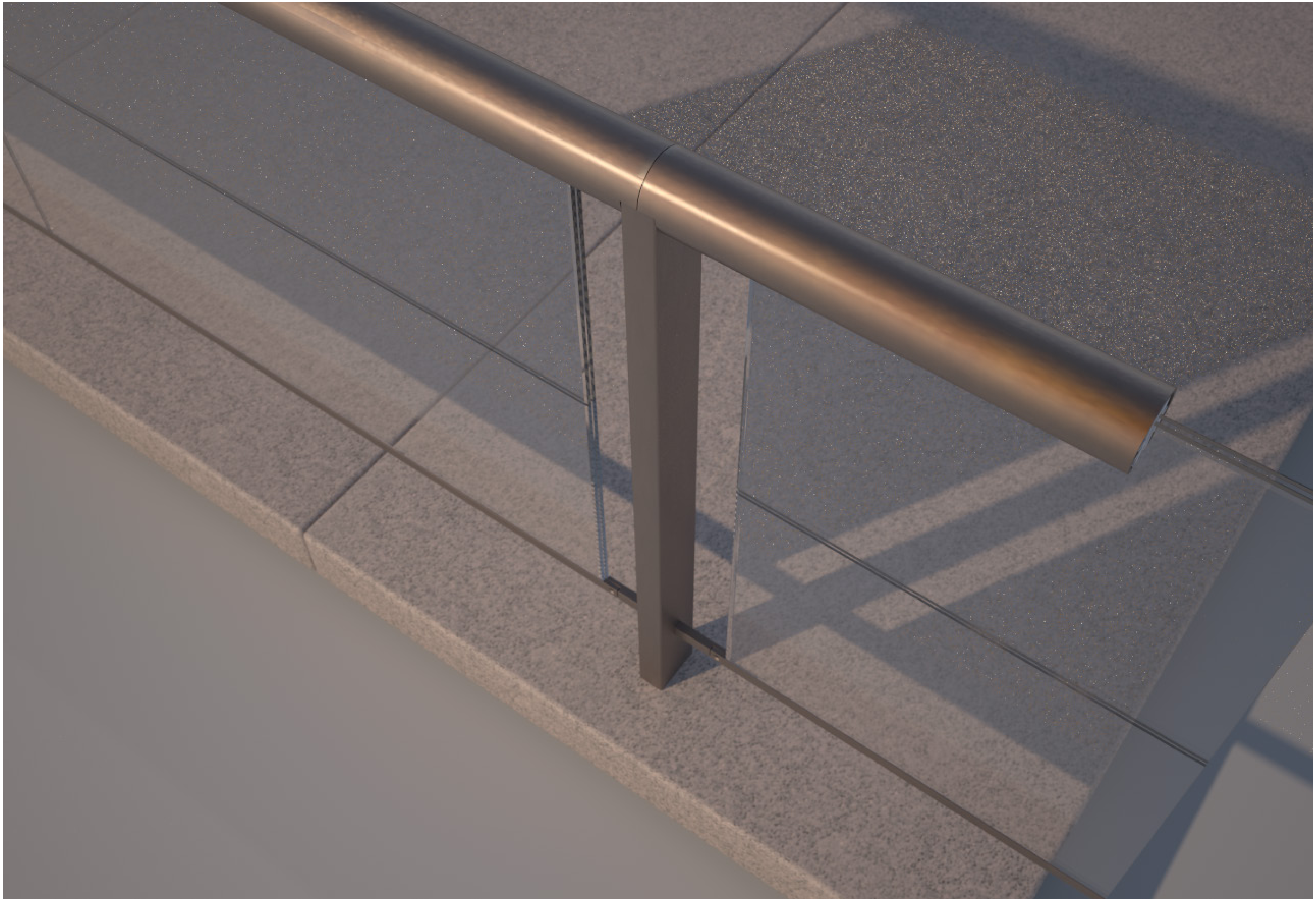
04



03

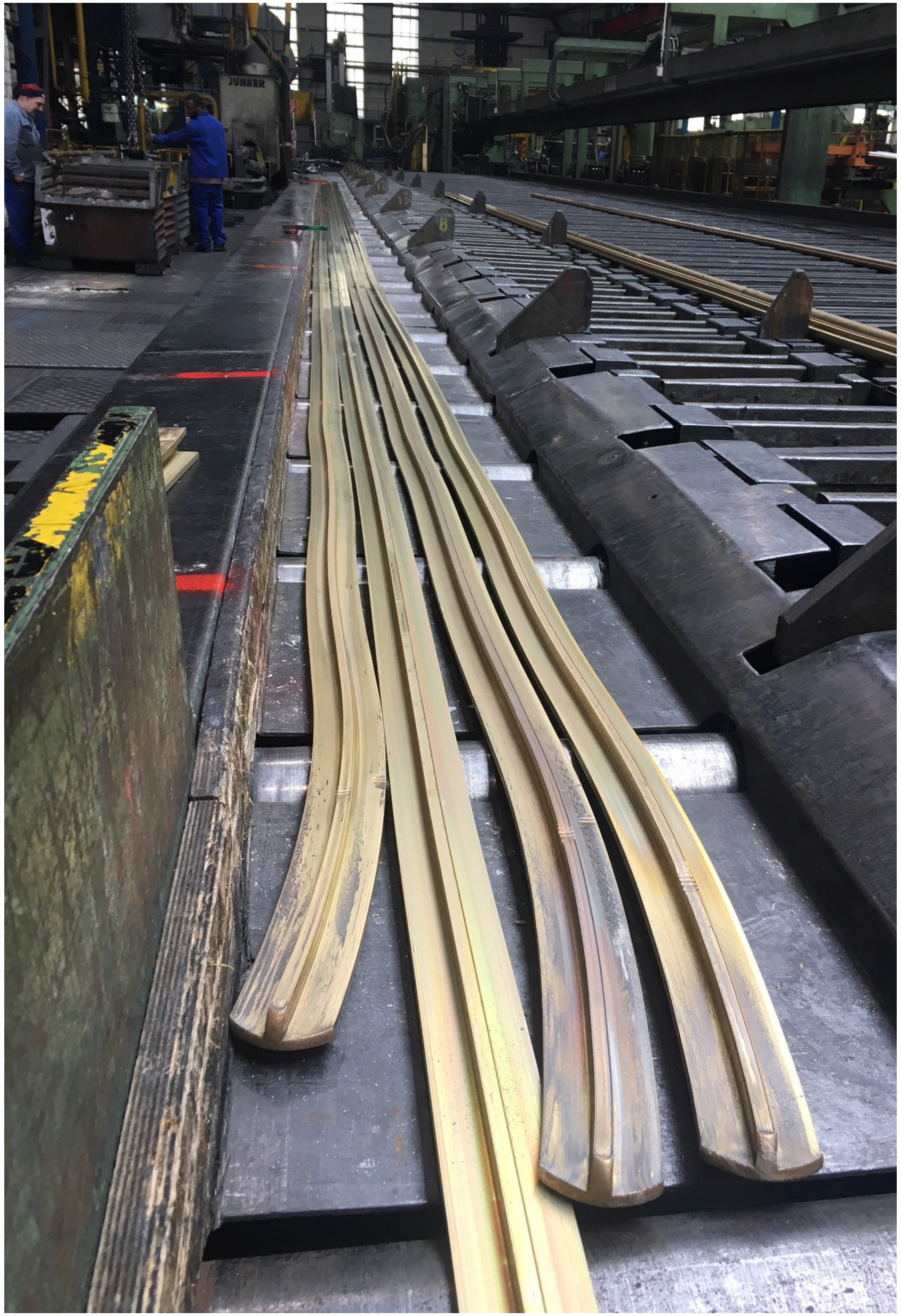
01 Glazed infill base restraint assembly.
02 Proposed Northern Foyer handrail.
03 Assembly studies of the glazing glamp.
04 Glazed infill base restraint.



02

Chapter 6

Materials & Process



Materials & process

Original facade and ironmongery elements were extruded from Austral 412 Manganese Bronze to form hand rails, glazing bars, grilles and louvres, door sections and thresholds. These architectural bronze componentry are “of high quality extrusion and finishing and [have] considerable heritage significance” (Report on the Maintenance Of Bronze Components, Sydney Opera House, Lucas Stuart, 2005).

There are several options that can be used to fabricate the required profiles. They are:

- Non-ferrous extrusion, can produce both hollow and solid shapes;
- Horizontal continuous casting, solid profiles;
- Sand casting, suitable for connection brackets;
- Roll forming / roller die forming; and
- 3D metal printing / selective laser sintering.

These manufacturing processes are outlined in the following section and considered within the context of the pros and cons of each process.

Austral Crane Copper - the original suppliers of these bronze extrusions to the Opera House - is no longer manufacturing extruded profiles and there are no alternative extrusion suppliers of copper alloys in Australia. This prompted a global search to investigate the capability of alternate suppliers who are still manufacturing architectural bronze. Initial contact was made through internet searches as well as input from Peter Webster, a technical consultant with the Copper Development Association UK.

Grimshaw has nominated a preferred supplier - Baoshida Swissmetal Ltd, and compiled a list of alternate potential suppliers with varying capabilities, different manufacturing processes and access to a varied range of copper alloys in the form of brass and architectural bronze.

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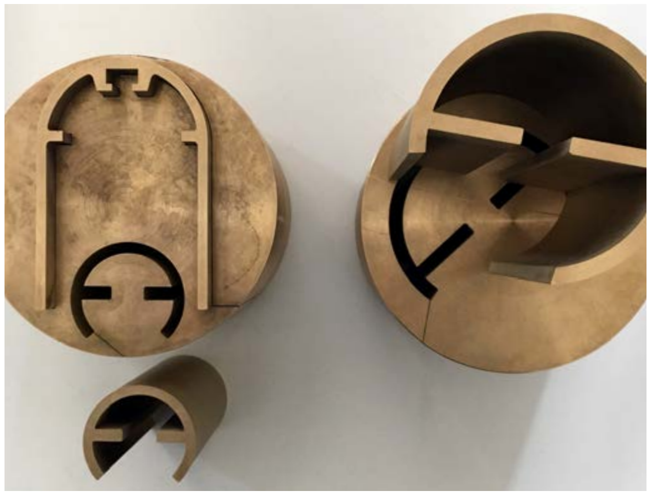
6.1

Bronze Alloy

01

03



02

01 Bronze billet, raw castings.
02 Full scale re-productions of the original U-Profile.
03 Bronze billet, Austral 412 reproduction.

Alloy selection
Austral 412

Retention of the original Austral 412 bronze alloy is considered critical to maintaining authenticity, but this custom alloy developed for the Opera House is no longer available. Over the years smaller upgrade projects requiring architectural bronze have not been able to procure the original specification of metal. Due to the size and scope of the current works requiring bronze extrusions, this specification calls for the re-creation of the original alloy due to the significance of the Sydney Opera House as a heritage listed building.

Tenderers provided pricing for two procurements options. The first accounted for the recreation of the original Austral 412 Alloy, in order to achieve it's mechanical weathering properties. Extruders also priced for and advised on their preferred alternate alloy, while providing evidence of it's mechanical properties and suitability for use in a marine environment.

As a result of the quantity of billet required for the works, the cost of the alternate alloy was determined to be similar to that of a custom Austral 412 alloy.

General

The following material specification is for the fabrication of handrails and barriers of internal works at the Sydney Opera House.

Fabrication Requirements

The majority of extrusions will be cut to length and finished with minimal fabrication, however there are fabricated components that are to be machined from extruded stock. These require CNC machining, and brazing to form the installed componentry for the handrail and barrier system.

There are some elements that fabricators may elect to cast to eliminate the fabrication of extruded components, it is important the tenderers of extruded profiles consider the suitability of the required alloy (or alternative alloy) such that it may be:

- Extruded;
- CNC machined;
- Brazed;
- Cast; or
- Forged.

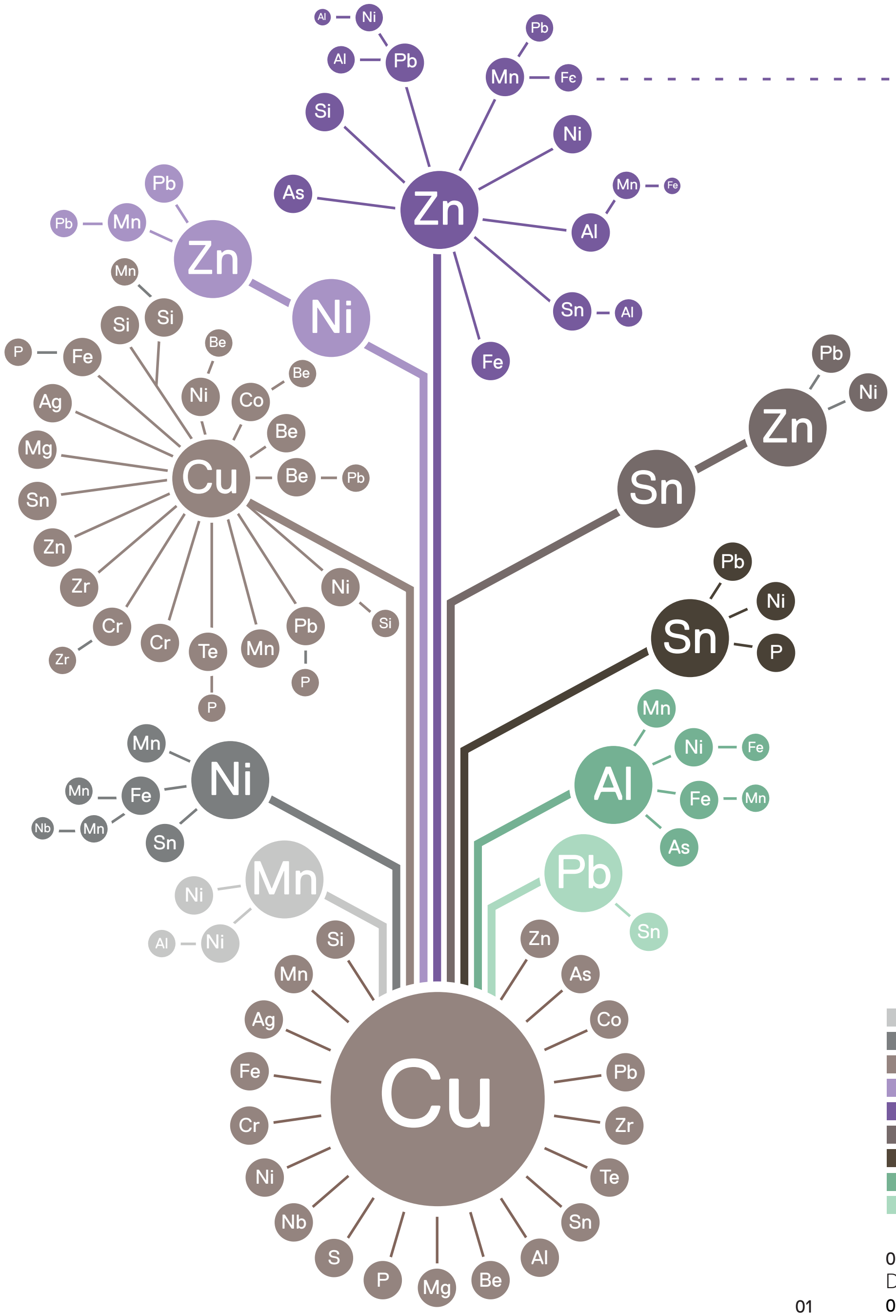
Architectural Bronze (Brass Alloy)

All structural bronze (brass alloy) components to meet the following minimum requirements:

- Minimum 0.2% Proof Stress - 240 MPa; and
- Minimum Young's Modulus (modulus of elasticity) - 103 GPa.

Elemental composition (approx.)

Element	Nominal composition (%)	Composition tolerance or range (%)
Copper	58.00	+/- 1.00
Lead	0.10	0.30 max.
Iron	1.00	+/- 0.20
Tin	1.00	0.30-1.00
Aluminium	1.00	+/- 0.20
Manganese	2.00	1.50 - 2.00
Other elements	0.50	0.50 max.
Zinc	Remainder	Remainder



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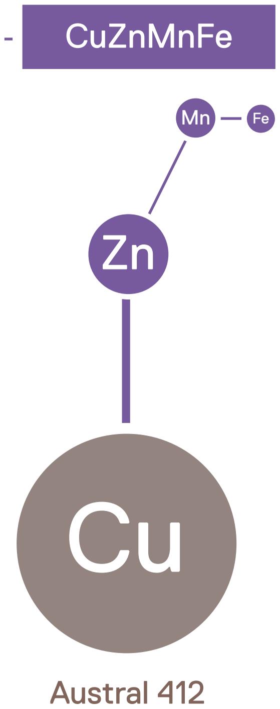
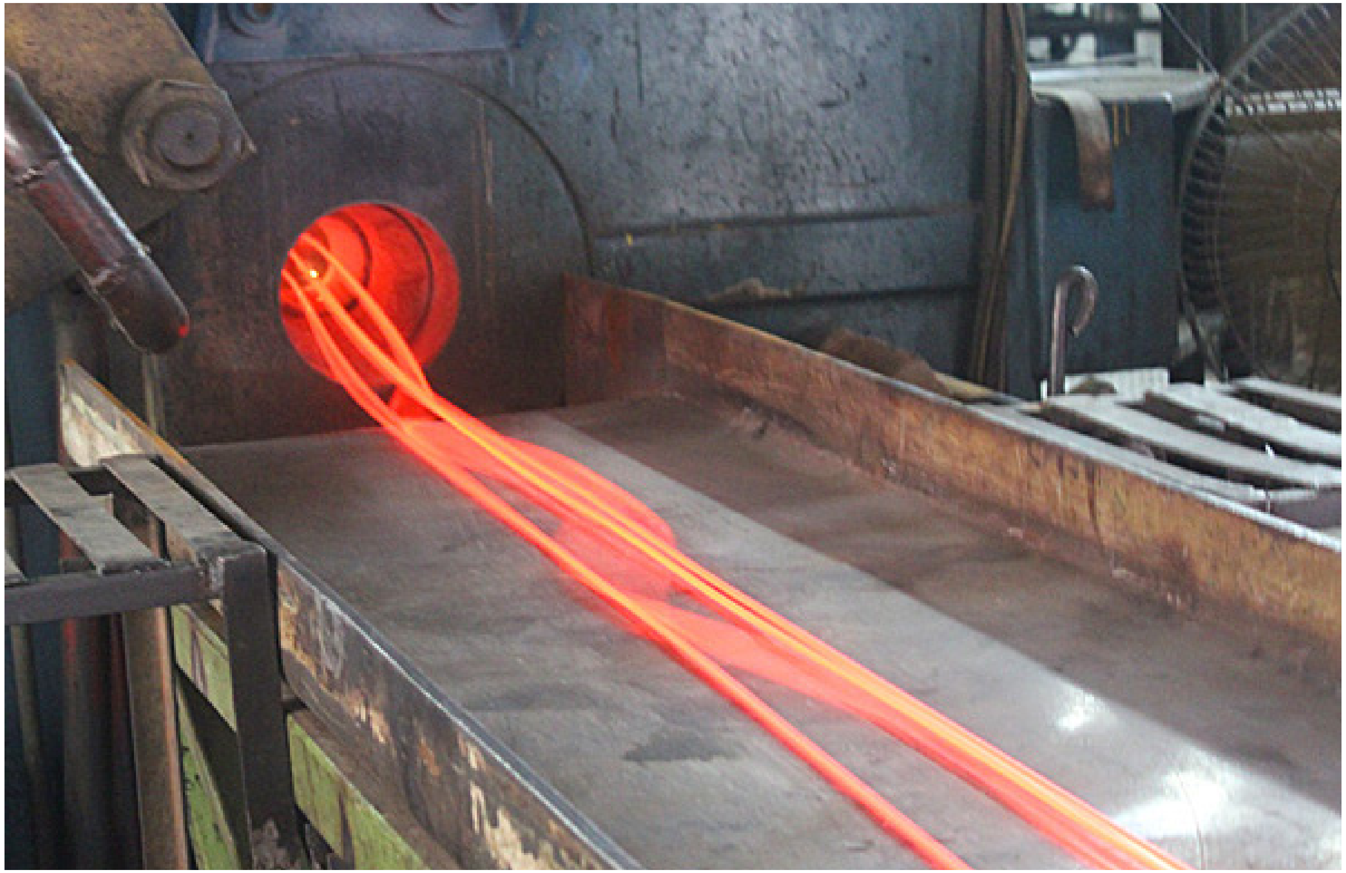


02

- Copper Manganese
- Copper Nickel
- Copper alloys
- Nickel Silver
- Special Brasses (includes *Austral 412) highlighted
- Copper casting alloys
- True Bronze
- Aluminium Bronze
- Leaded Bronze

01 Copper alloy tree. (Source data from diagram Copper Development Association UK with SwissMetal input.)
02 Alloy composition of Austral 412,



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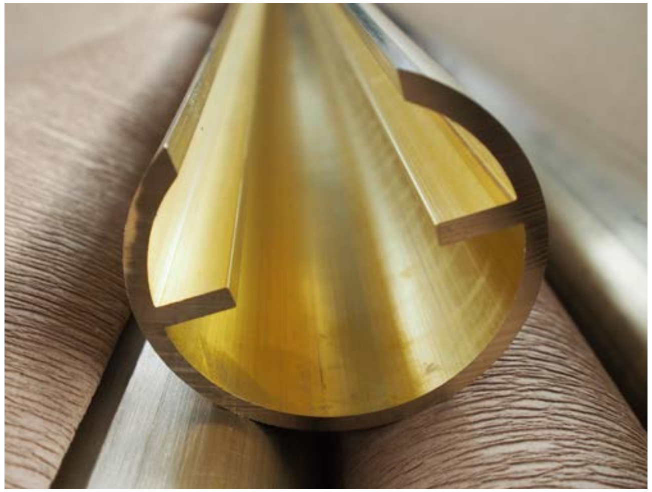
03



02

01 Architectural bronze extrusion process.
02 HB 01 80mm top rail with mill finish supplied by Baoshida SwissMetal, linishing and aging required during the fabrication process.
03 Billet production.

Architectural bronze alloy
Austral 412

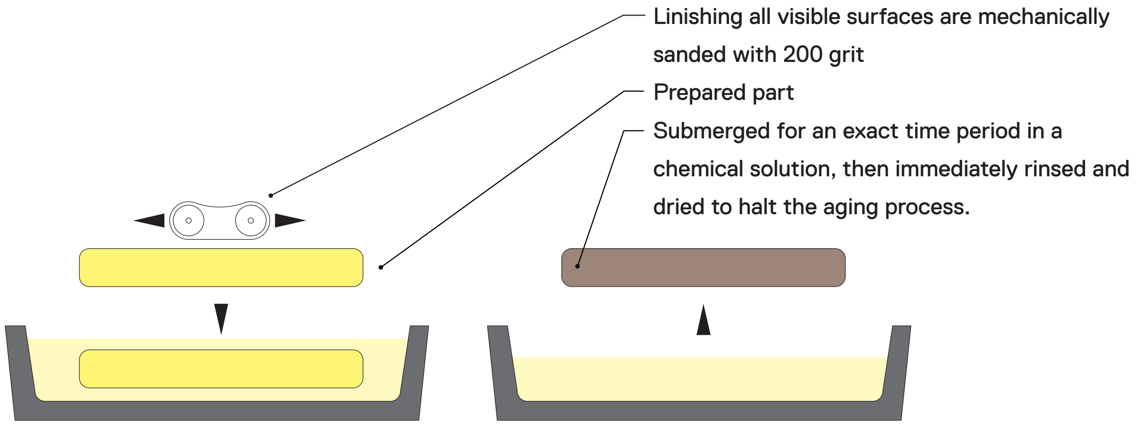
Extrusion profiles
The extrusion profiles required are illustrated in section 04 along with a drawing of the completed part. Some of these part drawings include machining processes that occur after the base extrusion profiles have been fabricated and will be managed by the selected local fabricator.

Essential min. mechanical properties
- 0.2% proof stress, minimum 240 MPa; and
- Young's (elastic) Modulus, minimum 130 GPa.

Required testing
- Chemical analysis of each batch; and
- Ultimate tensile strength. 0.2% proof stress and Young's modulus for each extrusion profile.

Although the initial order of extrusions for the current renewal works will be used inside the Sydney Opera House, the same profiles and alloy will be used on the exterior. Extrusions will be exposed to a marine environment and although the original alloy has acquired a natural patina, the extrusion for the Renewal Program will be linished and chemically aged to match the existing architectural metalwork.

Quality Sample
A sample extrusion from 2008, when exterior barriers were added to the Sydney Opera House, provided a benchmark for the level of surface finish required from the extrusion process (on the interior of the part) and the surface preparation required (by Sydney based fabricators) who will fabricate, linish and apply light chemical aging to the extruded profiles.



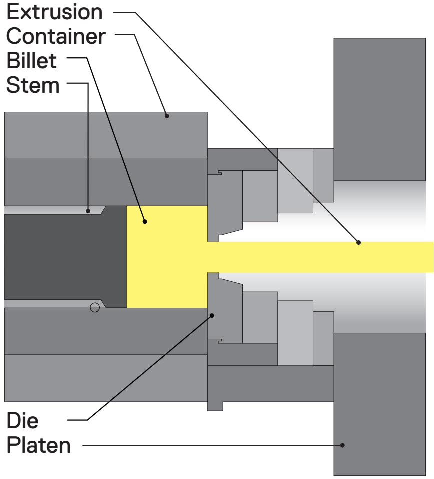
01

01 Linishing and aging process.

6.2

Manufacturing Process

01



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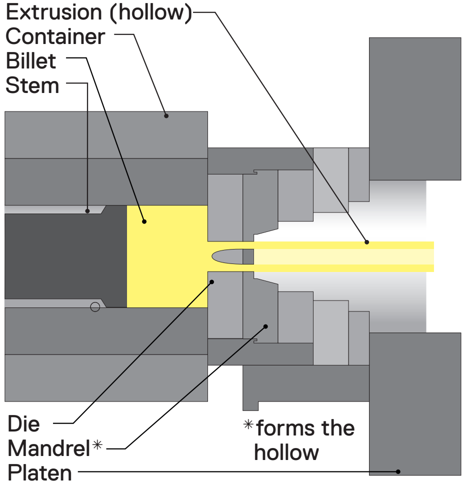


02

01 Extrusion die, the mandrel that forms the hollow is in the centre.

02 Extrusion process for hollow profiles.

03 Extrusion process for solid profiles.

Non-ferrous extrusion
Process

Extrusion is a hot working process. The heating process prevents work from hardening and makes it easier to push the material through the die.

The stock material in the form of a billet is heated and loaded into the container of the extrusion press. A hydraulic ram then presses on the material to push it out of the die.

The extruded profiles are initially cut to length until the billet material is exhausted. At this point a new billet is loaded and often the die is swapped for another to allow for cleaning and repair.

Afterwards the extrusions are stretched in order to straighten them.

Pros

- Efficient for large quantities;
- Consistent surface, minimal finishing;
- Alloy material properties are consistent; and
- Hollow sections can be produced via extrusion.

Cons

- Die development cost is high when minimal lengths are required;
- Profile size is limited by individual fabricators extrusion plant; and
- Not all extruders can produce hollow sections.

Horizontal continuous casting
Process

To begin, the casting crucible is furnace fed from a continuous melting source, the molten metal is maintained at the correct holding temperature in the crucible, which is completely enclosed.

Any dirt, dross or gases present rise to the top of the melt and are left behind in the casting process.

Acting as a riser, the metal prevents the formation of defects that may introduce imperfections in the final product.

During horizontal continuous casting, metal flows out the front of the crucible and into a water-cooled die where solidification takes place.

Drive rollers pull the bar along roller tables that support the weight of the bar while it casts. With precise control of temperature, the correct metal properties are created.

Horizontal continuous casting is a precisely timed manufacturing process. A traveling saw, synchronized with the ongoing continuous casting, automatically cuts the profile to a uniform length. The bars are then set onto cooling racks, ready for a mechanical straightening process.

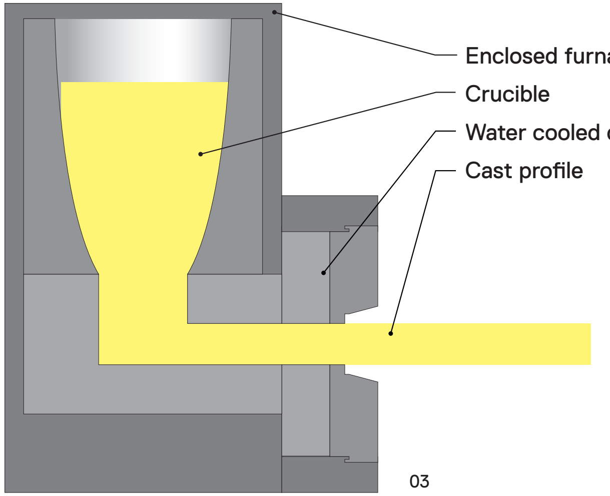
Pros

- Efficient for large quantities;
- Consistent surface, minimal finishing;
- Larger profiles are possible, up to 300mm;
- Longer lengths are possible; and
- Produces straight profiles.

Cons

- Alloy selection is limited as the crucible is part of the casting equipment and contamination can occur when changing alloys; and
- Only solid profiles can be cast, therefore integrated lighting could not be accommodated.

01



03

02

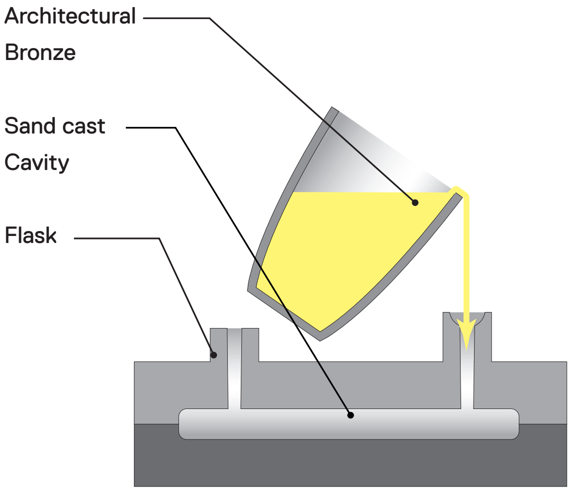
01 Casting process as the profile exits the die.

02 Casting process.

03 Horizontal continuous casting process.

01

01 Foundry process pouring into multiple flasks.
02 Sand casting process - part removal.
03 Sand casting process - mould preparation and casting.



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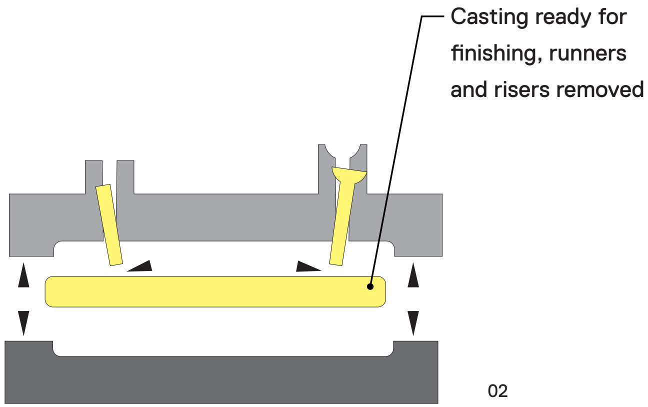

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Sand casting
Process

Sand casting, also known as sand-moulded casting, is a metal casting process characterized by using sand as the mould material.

The majority of all metal castings are produced via sand casting process, as it is a relatively cost effective and flexible method of producing complex metal forms.

The sand is typically contained in a system of frames or mould boxes known as a 'flask'. The mould cavities and gate system (cavities used to deliver the molten metal) are created by compacting the sand around models, or patterns, or carved directly into the sand.

During the moulding process the flask is split in two, so that the patterns can be removed. This removal process can limit the shapes that can be used and all flat surfaces require a "draft angle" that allows the pattern to separate from the sand mould.

The molten alloy is then poured into the hollow mould cavity of the desired shape where it solidifies. The casting is removed from the mould for processing where the runners and risers that allowed the metal to be delivered to the mould are cut away.

Surface treatment and finishing is required to conceal the riser and runner attachment points and may be necessary to remove the surface finish left by the sand casting process.

Pros

- Efficient for small quantities;
- Can accommodate multiple shapes and profiles with complex surface geometries; and
- Alloy selection is flexible.

Cons

- Castings require intense surface finishing;
- Material properties not consistent due to contamination of gasses;
- Surface finish susceptible to pitting; and
- Limited to short lengths, too short for application at the Sydney Opera House.

Roll forming
Process

The initial step for roll forming is to extrude a thin walled tube from the required copper alloy, which is then processed into the required profile.

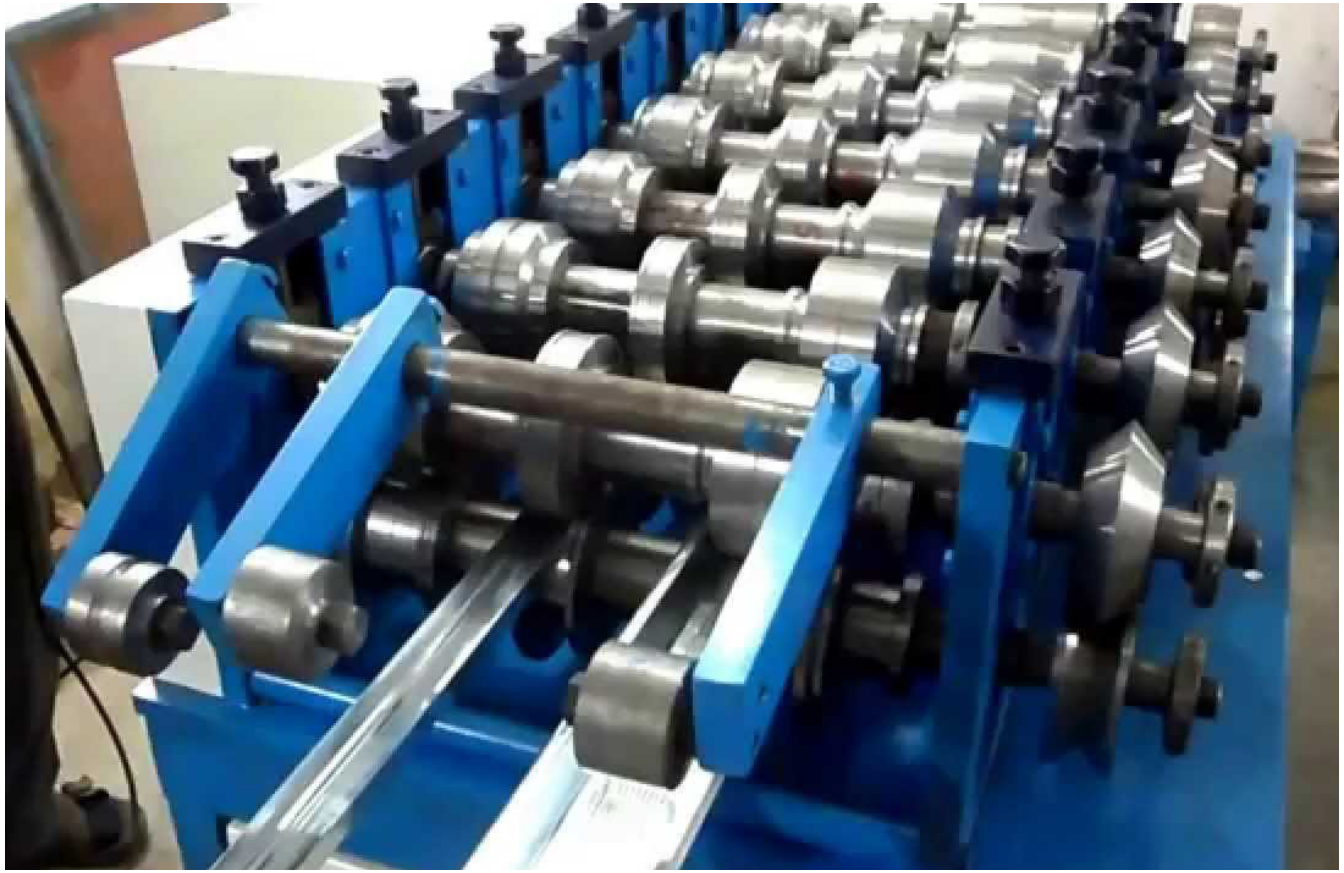
The roll forming process works by passing the extruded tube through a series of rollers, with each of these rollers adding shape to the metal as it passes through. The rolls work together to form the desired cross section. Since the process is consistent and easy to repeat.

One of the production limitations is the original tube section must remain in tact and depending on the profile required may limit the options available, especially if thicker walled structural sections are required.

The roll forming process is most suitable for simple non-structural profiles, the straight forward tooling allows for low-cost, high volume production.

Pros
- Cost effective;
- Consistent surface finish;
- Large profile sizes are possible 140mm; and
- Can accommodate multiple shapes and profiles.

Cons
- Limited to thin wall sections, not suitable for the barrier loading requirements of the Sydney Opera House; and
- Cannot accommodate profiles that are complex in cross section.



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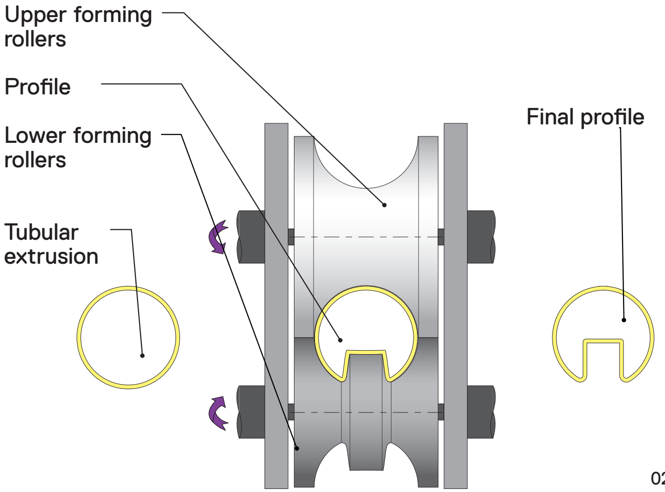
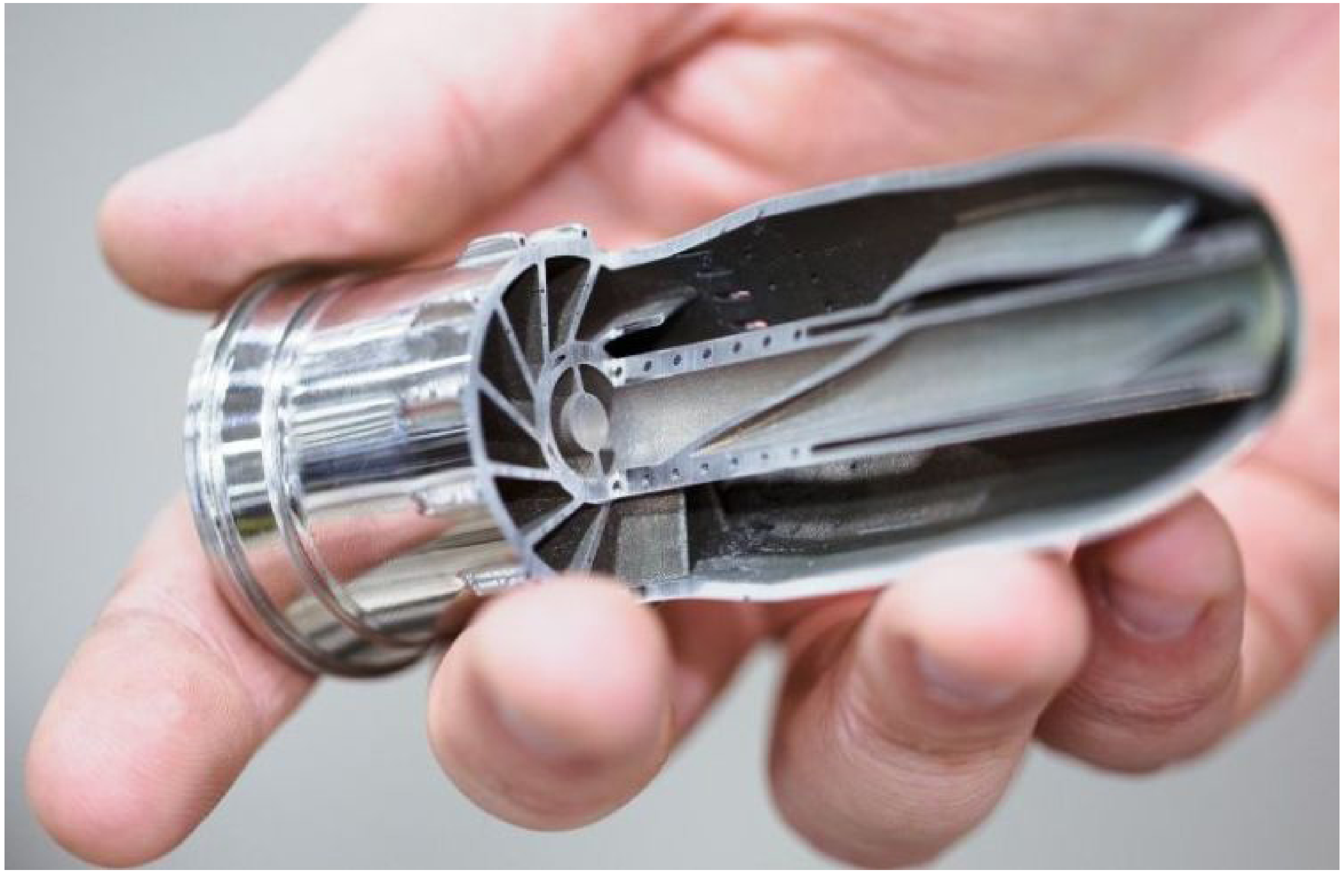


02

01 Progressive rollers form the profile into the desired shape.

02 Roll forming process illustrating the upper and lower rollers.



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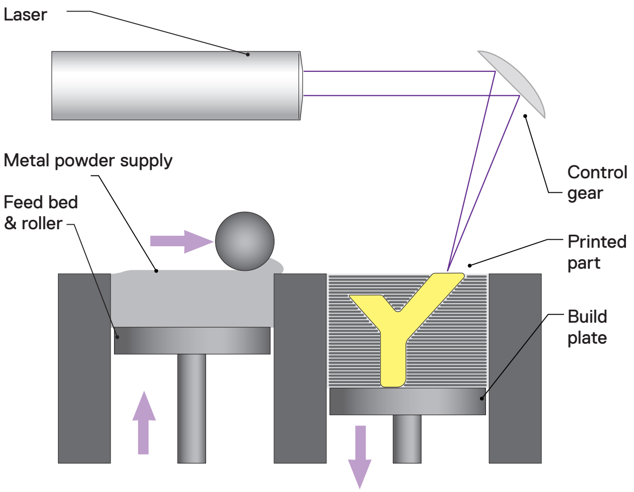


03

02

01 Multiple metal powder layers fuse to form the desired shape.
02 Example of 3D printed bronze part.
03 3D Metal printing - laser sintering process.

3D metal printing / selective laser sintering
Process

3D metal printing is an additive manufacturing process that allows production parts to be generated in metal from a CAD model.

The printer uses a heated chamber to hold a bronze metal powder slightly below its meting point, then the selected areas of the powder are precisely melted by the laser. This process is repeated building up, layer by layer, until the build is complete. Only the material fused by the laser is used in the process and the remaining powder supports the part as the print layering progresses.

After the print has been formed, it is removed for post processing. The support structure is removed, leaving the final printed product.

Pros

- The printing process generates functional parts;
- The ability to quickly produce unique parts;
- Mass customisation eliminates the need for moulds or repetitive fabrication techniques;
- Consistent metal properties throughout the completed part; and
- Can accommodate multiple shapes and profiles.

Cons

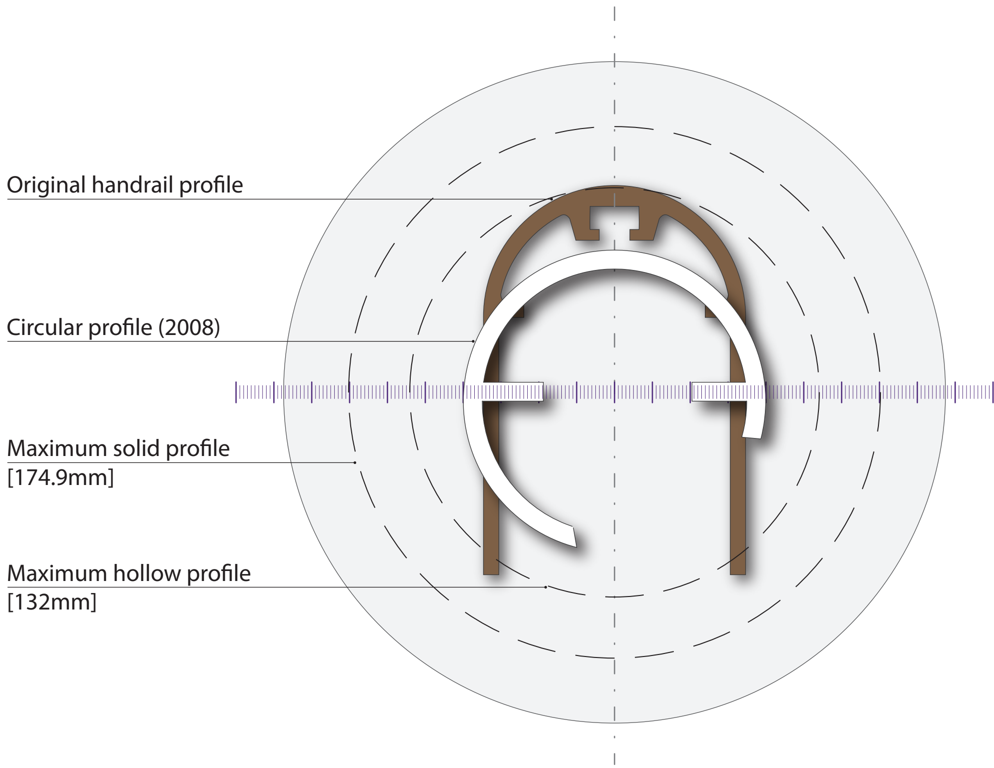
- Limited to size of the print bed .i.e. only suitable for node component;
- It is unknown if the Opera House alloy can be made into the specialist powder required for 3D metal printing; and
- Specialist equipment, grinding and wire EDM machines required to remove support structures.

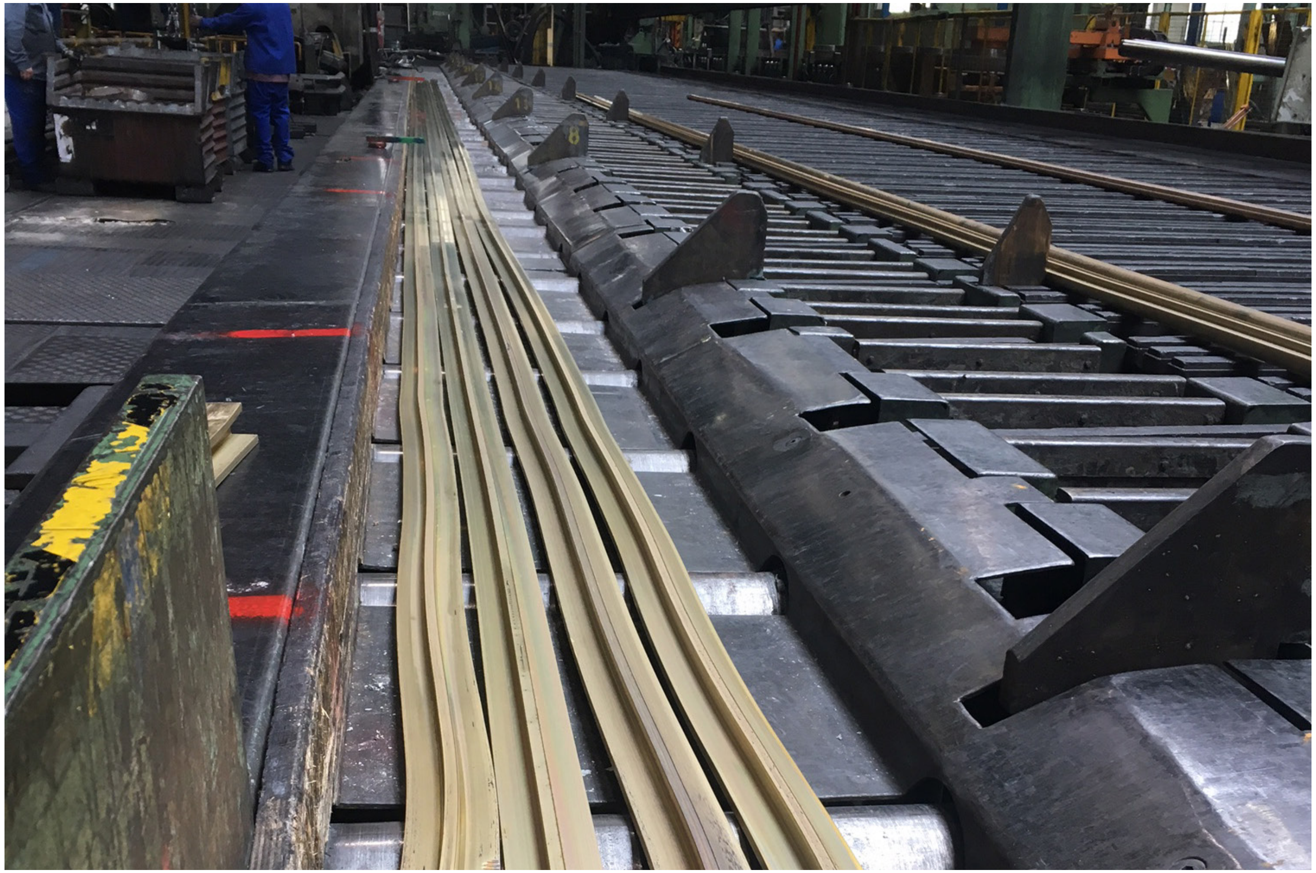
6.3

Extrusion Suppliers

Nominated extrusion supplier
Baoshida Swissmetal Ltd.

Country:	Switzerland
Location:	Grand Rue 62 732 Reconvilier, CH
Website:	www.baoshida-swissmetal.net
Contact name:	Mr. Philippe Michel Philippe.michel@swissmetal.com Tel +41 61 705 32 20 Mobile +41 79 249 44 11
Process:	Bronze alloy foundry Bronze alloy extrusion Bronze alloy forging
Max. extrusion	Solid: 174.9mm diameter Hollow: 132.0mm diameter
Notes:	Information on extrusion profile sizes and alternative alloy information was provided by Baoshida Swissmetal. Swissmetal were the extrusion supplier for the Western Concourse project in 2008. Examples of their profiles are in storage in the form of new / old stock at the Opera House St. Peters storage facility. Base metal limit for the production of a custom alloy is 6T. This involves cleaning of the crucible and furnace and careful monitoring of the process to ensure the specified alloy is achieved





01

03

02

01 Extrusion production, HN-02 profile.
02 Extrusion production, IN-01 profile.
03 Die & mandrel forming the interior and exterior of extrusion.

Global search
Extrusion suppliers

Supplier	Country	Address	Website	Contact	Process	Max. Extrusion ø	Notes
Amari Copper Alloys	United Kingdom	Unit 47 Eagle Road Moons Moat North Redditch Worcs B98 9HE, UK	www.amaricopperalloys.com	Bob Cadwaladr bobcad@amaricopperalloys.co.uk Tel: +44 (0)1527 405600	Brass alloy extrusion	Solid: TBC Hollow: TBC	Confirmation of alloys used: CW721R, CZ114.
AW Fraser Ltd.	New Zealand	39 Lunns Road, Middleton 8024 Upper Riccarton 8442 Christchurch, NZ	www.awfraser.co.nz	Chris Moffat chris.moffat@awfraser.co.nz Tel: +64 3 341 0027	Brass alloy extrusion	Solid: 50mm Hollow: N/A	Discussed foundry requirements and toiling process of metals recycling.
Avins USA, Inc.	United States	242 Old New Brunswick Road, Suite 415 Piscataway, New Jersey 08854 USA	www.avins.com	Joe Rudden, Jr. jrudden@avins.com Tel: +1-310-699-2760	TBC	Solid: 174.9mm Hollow: 121mm	Base metal limit for custon Alloy production is 6T, production of extrusion split between sites depending on profiles sizes.
Buntmetall Amstetten GmbH	Austria	Fabrikstr. 4, 3300 Amstetten, AU	www.buntmetall.at	office@buntmetall.at Tel: +43 (0)7472 606	Brass alloy extrusion	Solid: TBC Hollow: TBC	No information received.
Cidneo Metallurgica SPA	Italy	Via Cavicchione Sopra, nr. 65 I-25011 PONTE S.MARCO - BS, IT	www.metallurgicacidneo.it/	Forelli Dott.ssa Carlotta cforelli@metallurgicacidneo.it Tel: +39-030-5538100	Brass alloy extrusion	Solid: 120mm Hollow: N/A	Confirmation of alloys used: CW618N, CW624N, CW617N, CW723R, CW720R. Extrudion tollerance info provided.
Deeco Metals	United States	655 North Main Street Travelers Rest, South Carolina, 29690 USA	www.deecometals.com	Randy Klein randy@deecometals.com Tel: +1 (864 610-1032 ext 206	Brass alloy extrusion Brass alloy forging	Solid: 101.6mm Hollow: N/A	Information on extrusion profile sizes received.

Supplier	Country	Address	Website	Contact	Process	Max. Extrusion ø	Notes
Filto Profiles	Spain	Polígon Industrial Can Prunera, Carrer Solsonès 14 / 08759 Vallirana, Barcelona, SP	www.filto.com	Julián Carreras filto@filto.com Tel: +34 93 683 42 56	Brass alloy extrusion	Solid: 100mm Hollow: TBC	Lead times: Die development: 14 days Production: 14 days Shipping: 45 days Alloys used: CW622N,CW624N, CW614N, CW617N, CW618N, CW603N, CW605N, CW508L and CW721R. Filto Profiles do not produce hollow extruded profiles. They offer an alternate method, using two solid profiles joined with dovetail connections. The resulting hollow profile used two cheaper dies but results in a visible seam.
Lewis Brass & Copper Company	United States	69-60 79th Street Middle Village, NY 11379 USA	http://www.lewisbrass.com	sales@lewisbrass.com +1 (718) 894-1442	TBC	Solid: 90mm Hollow: 90mm	Profiles sizes we require are at the limit of this fabricators capacity. Future larger profiles would need to be done in parts and joined or by another extruder.
NFM Extrusion Division	South Africa	Non-Ferrous Metal Works 1 Avenue East, Prospecton Durban, SA	www.nfm.co.za	Zane Havemann zaneH@nfm.co.za Tel: +27 31 902 7470 Cel: +27 83 3011 859	Brass alloy extrusion Brass alloy foundry	Solid: 112mm Hollow: 90mm	Information on extrusion profile sizes and foundry information received.
Trefimetaux	France	11 bis rue de l'Hôtel de Ville92411 Courbevoie Cedex, FR	www.tmx-france.com	brass.rods@kme.com Tel: +33(0)1 47 89 68 20	Brass alloy extrusion	Solid: TBC Hollow: TBC	No information received.
Wieland-Werke (UK) Ltd.	United Kindgom	Pennard Close, Brackmills Northampton, NN4 7BE, UK	www.wieland.de	Aljoscha Lemberg aljoscha.lemberg@wielanduk.co.uk Tel: +44 (0)1604 667644	Brass alloy extrusion	Solid: N/A Hollow: 140mm	Only hollow tube production, limited to simple forms. Extruded first as thin walled tubes. Sections are produced by tube forming process. Progressive rollers form desired shape.

Summary & Conclusion

Summary & conclusion
Looking back and moving forward

The Volume 1 Design Investigation presents a compendium of past research and new findings that form the framework for the design parameters underpinning the Volume 2: Design Manual. Learnings from the Design Investigation outline the key conditions, constraints and opportunities that must be addressed by future barrier and handrail design, and establish design criteria and evaluative tools to weigh a range of solutions and processes appropriate to future work at the Opera House.

Ultimately, the preferred barrier and handrail assemblages, recommended materials, and processes presented in this Volume reflect the outcomes of a carefully considered and consultative Design Investigation study phase.

Findings from the Existing Document Appraisal support design solutions that reflect the standards of excellence and design integrity outlined by the guiding Utzon Design Principles and key heritage and conservation documents. Key new learnings from additional documents have also informed the recommended designs and processes, notably:

- Government architect plans have provided a basis for the project's crowd loading categories;
- Reviews of past extrusion suppliers have established benchmarking information based on the standard of the 2008 supplier as a base reference; and
- Older schemes once deemed too expensive - for example the Opera House integrated lighting system as proposed in the 2009 Stage 1 Working Group Report (Document 09) - have been reconsidered and, where feasible, recommended for implementation in light of new technological and costing realities.

Site visits and the audit of the Opera House's storage archive also generated outcomes that have direct application for the Design Manual:

- Original samples of the 2008 bronze material established benchmarks for linishing and aging; and
- Historical examples of the welded connections were deemed appropriate for future works and recommended to be carried forward.

Both the interior and exterior preferred options respond to and respect the heritage significance of the Opera House, and employ materiality and craft for fabrication which has made it a world class building. Throughout the design of the handrail and barrier system, the requirements of the interior and the new design were continually measured against the geometries of the exterior stair, ramp and podium. This ensured that the base system - consisting of a post, top rail and integrated handrail - could accommodate future deployment and use. Additionally, this process informed the barrier infill design. As a point of difference, the interior assembly uses an elegantly supported plane of low iron glass throughout the house, while on the podium, tension rods are fixed with concealed turnbuckles, or tensioning devices, within the top rail.

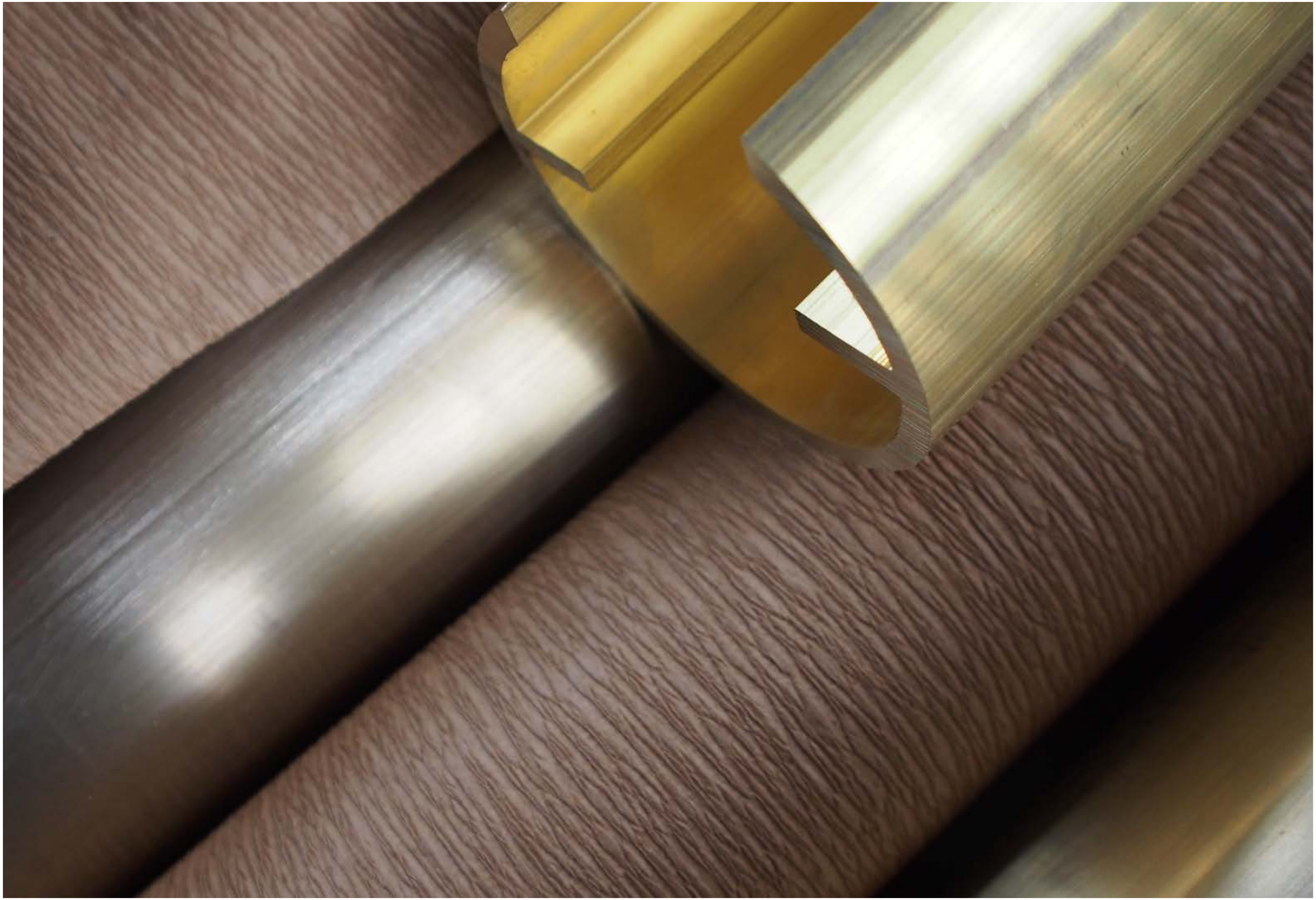
Finally, the recommendations of Volume 1 regarding materials and manufacturings process are as follows:

- Retention of the conventional extrusion manufacturing process, in consideration of ease and cost;
- The nomination of extrusion supplier Baoshida Swissmetal Ltd, (also the supplier of the 2008 extrusions); and
- Use of the original bronze alloy Austral 412, with the quantity of material required for the project allowing for reproduction of this custom alloy at a comparable cost to that of an available alternative.

The Design Investigation establishes an approach and series of understandings and recommendations for the design, manufacture and implementation of bronze componentry that respect and celebrate Utzon's vision and legacy. It's findings ensure that there is a holistic and long-standing reference framework in place to guide the quality and integrity of bronze componentry in such a way that considers both the current and future needs of the Opera House.

Moving forward, the Volume 2 Design Manual provides an implementation guide for a new barrier and handrail typology across the Opera House. This typology is positioned to respond to the complex stair and plan geometries at site, while allowing for an adaptable assembly that can accommodate interior and exterior conditions.

Taken together, Volumes 1 and 2 of the Bronze Componentry Project provide an invaluable guide to architects and consultants of current and future building upgrades and exciting new projects to come.



Team acknowledgments

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Arup

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GRIMSHAW

PRISM Façades | ARUP