Australian Earthquake Engineering Society
National Conference, 21-23 November 2024
Adelaide, South Australia

Sydney Modern – Seismic Design of a New Gallery over Existing Infrastructure

Andrew Phillips (andrew.phillips@arup.com), Andrew Johnson (andrew.johnson@arup.com), Michaela Brown (michaela.brown@arup.com), Gerard Taig (gerard.taig@arup.com), Matthew Walden (matthew.waldem@arup.com)

Arup, Level 5, 151 Clarence Street, Sydney, NSW, 2000, Australia

Abstract

The Sydney Modern Project has almost doubled the floor space of the Art Gallery of NSW.

The new building comprises a series of linked steel-framed pavilions over a concrete podium, set in an excavation in a hillside. Approximately 2/3 of the new structure is built over existing infrastructure; partly a 'land bridge' over the Eastern Distributor motorway, and partly a pair of decommissioned subterranean Navy fuel tanks.

The complexity of the architectural form, and the requirement to use existing structures to support a new building, required an innovative approach to the seismic design.

The building is partly supported by the land bridge under gravity, while the stability system is founded on natural ground. In order to compromise the stability of the land bridge, the new structure is isolated laterally from the bridge by slip joint bearings.

A conventional analysis was not sufficient to optimise the stability design, so a Non-Linear Response History Analysis was undertaken. As well as minimising risk in the seismic performance, this analysis allowed the minimisation of steelwork and reinforcement in the stability system.

Keywords: Non-Linear Response History Analysis, Seismic isolation, Performance-based design, Heritage structure.

1 Introduction

The Sydney Modern Project has transformed the 153-year-old Art Gallery of New South Wales (AGNSW) into a two-building art museum; with the addition of a new building Naala Badu (Aboriginal language name meaning ‘seeing waters’) to the north of the original building Naala Nura (‘seeing Country’).

Arup was the structural engineer for the project, and also undertook civil engineering, acoustics, fire engineering, hydraulics/fire services engineering, lighting design, security consulting, pedestrian modelling and traffic planning services.

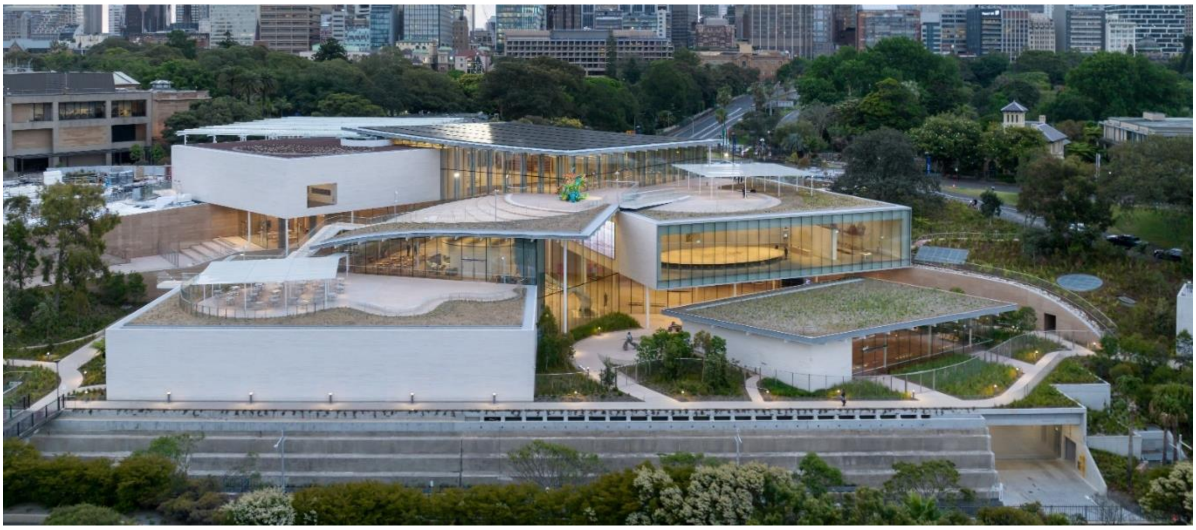

Figure 1 – Naala Badu – The new north building of AGNSW (© Iwan Baan)

2 Project Description

Japanese architectural firm SANAA, with local firm Architectus, designed the new building to respond to the site’s topography and integrate with existing infrastructure. The project site is on a steep escarpment in The Domain parkland on the east of Sydney’s CBD, north of the original Art Gallery building.

The new and original buildings are separated by a 'land bridge’ built in 2000 over a multi-lane freeway built in the 1960s, the Eastern Distributor. Adding complexity was a pair of decommissioned Navy fuel tanks below the site, built in a former sandstone quarry during WWII to service ships at the nearby naval base.

The new building comprises interlocking art pavilions nestled into the landscape over five levels, partially resting on the land bridge and the fuel tanks. Each pavilion connects with the outdoors, via roof terraces, walkways, and landscaped gardens.

SANAA’s concept was for a light and expansive design that provides new types of spaces to enhance the presentation of art, performance and learning facilities. A particular feature is a new prominent destination for Aboriginal and Torres Strait Islander art and culture, both inside the new building and across the campus, including a major commission in the art garden that links the new and original buildings.

The new building was realised through a collaboration between the Art Gallery and Infrastructure NSW (INSW). It was delivered by lead contractor Richard Crookes Constructions (RCC).

Figure 2 – New building Naala Badu, with land bridge over Eastern Distributor motorway (running top right to bottom left), and original building Naala Nura top left (© Iwan Baan)

3 Structural Scheme

The new structure consists of a series of linked steel-framed pavilions and canopies, built over a reinforced/post-tensioned concrete podium, set into in a deep excavation into the hillside.

The steel-framed pavilions include steel-composite floors and roofs. Visible columns are slender thick-walled circular hollow section (CHS), while those concealed in walls are universal columns (UC). Global lateral stability is provided by reinforced concrete (RC) shear walls and cores, while each pavilion has its own internal stability system. Where possible, vertical bracing concealed in perimeter walls is used, but this was not possible in the building's Entry Pavilion, due its continuously glazed façade which the architects did not wish to interrupt with bracing, so it was designed as a two-way steel sway frame. Similarly, three large glazed steel canopies are stabilised by a combination of portal and cantilever action to avoid bracing.

Much of the building is founded on the existing structures of the fuel tanks and the land bridge. The project has transformed the southern of the two tanks into an immersive art space of 2200m2. The Art Gallery's intent was for this space to be left 'raw', with the only spatial interventions being a new floor slab with sub-floor drainage, openings cut into the walls for egress, and a circular penetration in the roof slab for a new spiral steel stair.

The land bridge partially supports two pavilions, the Welcome Plaza and its canopy, an 'art garden' and extensive landscaping.

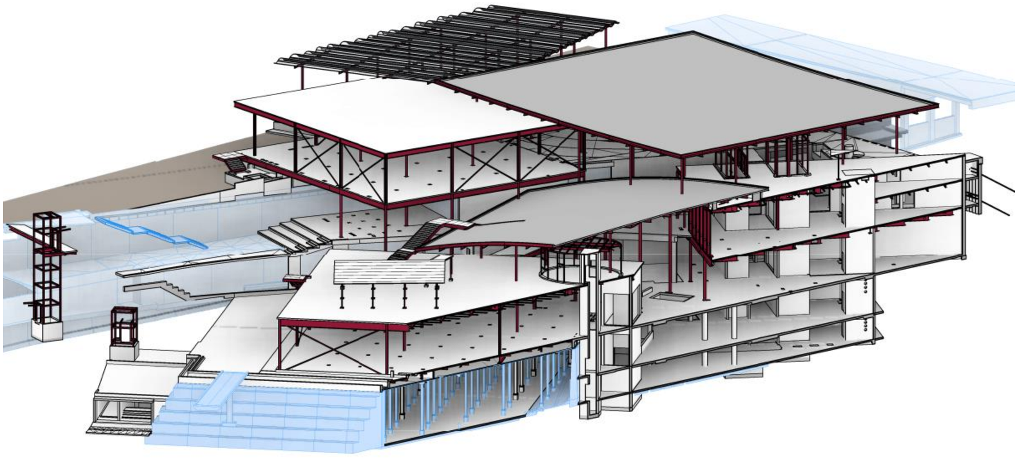

Figure 3 - Section from structural Revit model; fuel bunker at bottom left-centre & land bridge at rear.

Repurposing Existing Structures

Regenerating and reusing the existing structures on the site was integral to the evolution of the new gallery building's form and success as a project.

The location chosen for the project was far from a greenfield site. Site constraints meant that more than 2/3 of the new building had to be founded on existing structures. This included the Navy fuel tanks and the Eastern Distributor land bridge. The new structures over the existing were designed to be as light as possible; steel-framed where practical, with lightweight concrete of 1880kg/m3 density and 30MPa strength used extensively in floor, roof and wall structures. The reduced self-weight, and strategic arrangement of structures to control load paths, enabled the structural team to achieve the imposed loads prescribed by the Art Gallery, while minimising impacts on the existing structures.

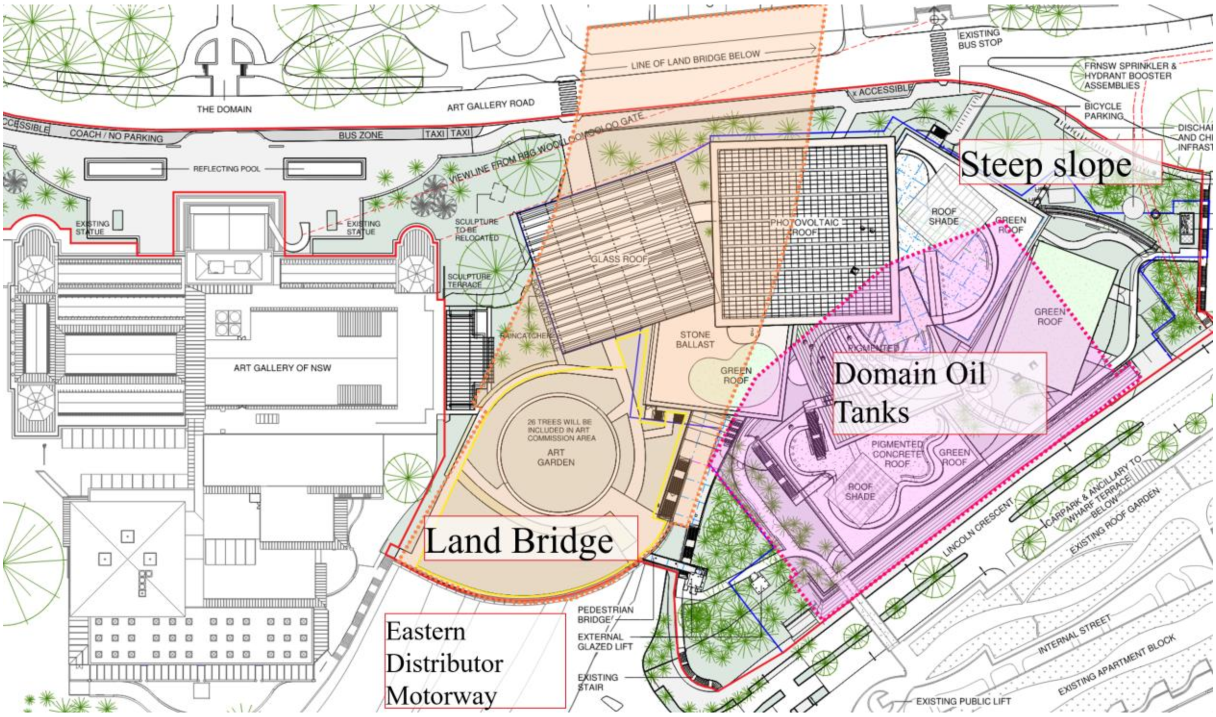

Figure 4 – Site plan showing footprint of new building (blue outline) over existing structures; Eastern Distributor land bridge on left and fuel tanks on right. Arup, based on drawing by SANAA.

Eastern Distributor Land Bridge

The land bridge was built in 2000 as a public domain improvement as part of the Eastern Distributor project, primarily a road tunnel project which included widening of the existing Cahill Motorway which ran in a cutting next to the Art Gallery. It was a suitable location for part of the new gallery building due to its proximity to the original building.

The Welcome Plaza and its glazed canopy, the entry pavilion and Aboriginal and Torres Strait Islander 'Yiribana'gallery are all located partially on the land bridge. In order to avoid road closures during construction and to control costs, no strengthening or other alteration of the land bridge to enable the construction of these structures was permitted.

Based on assessment of the as-built drawings, construction records, and known construction sequence, the Arup team developed a capacity diagram that was utilised to develop the massing of the new building, the landscaping, tree and sculpture allowances, and then to plan and review the construction loading. The team used the capacity diagram to determine the best positioning and structural systems for the portion of the new building over the land bridge.

The floors over the land bridge are lightweight concrete slabs on two-way lightweight concrete walls, designed to optimally distribute the loads across the precast bridge girders and avoid overloading any elements. These floors support steel-framed pavilions with composite steel-lightweight concrete roofs. The floors act as diaphragms to connect laterally with the global stability system (located off the land bridge), and isolated laterally from the land bridge structure by simple sliding bearings under the supporting walls. This allows the building to move independently from the land bridge during a seismic event, protecting both structures and avoiding retrofitting of the land bridge.

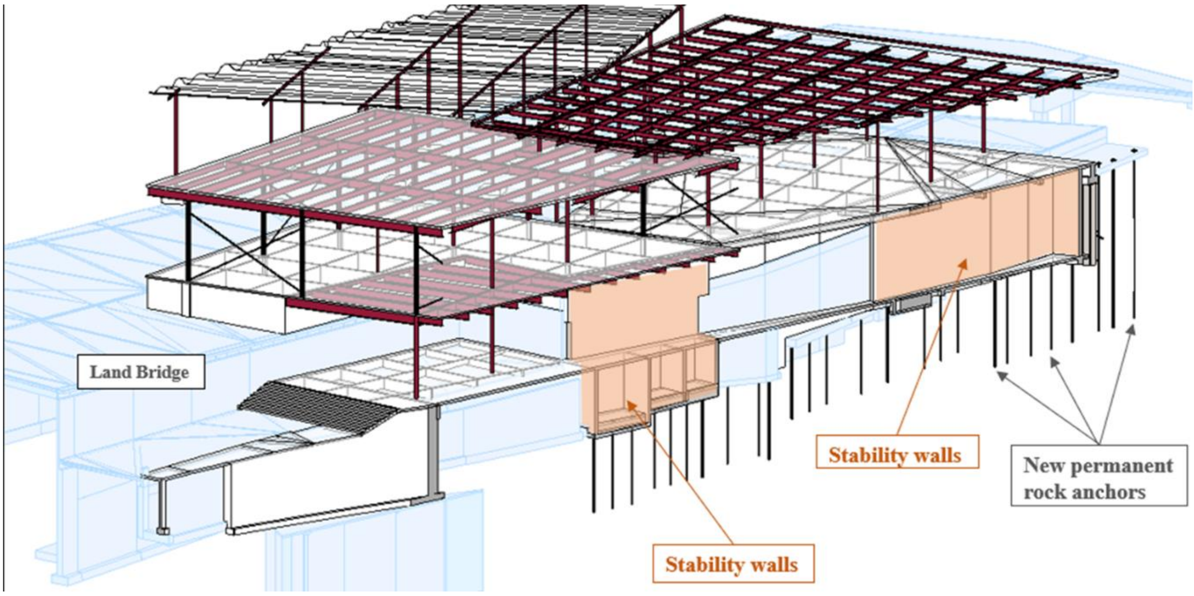

Figure 5 - 3D view from Arup structural Revit model, showing portion new structure built over land bridge (blue), connecting to stability walls (orange) founded on rock off land bridge.

Construction of the new structure next to the land bridge required excavation of much of the existing hillside. Although the deeper parts of the excavation were in sandstone, there was a considerable quantity of fill near the surface, including against one of the land bridge abutments, a long RC retaining wall. Since removal of the fill over the wall toe could destabilise it under seismic actions, vertical rock anchors were installed through the toe at regular centres as excavation proceeded along its length, providing permanent resistance to overturning.

Navy Fuel Tanks

During World War II, two large reinforced concrete bunkers, approximately 50m x 50m long and 7m high and separated by a dividing wall, were built on the site of a former sandstone quarry, to store fuel oil for the Royal Australian Navy fleet at the nearby Garden Island naval base. The bunkers were decommissioned in 1983, and residual fuel removed. These tanks lay under a large portion of the site chosen for the art gallery expansion.

To accommodate a loading dock and back-of-house functions for the new building, the roof slab of the northern tank was demolished, with most of the perimeter walls and the raft foundation retained. A two-storey structure with post-tensioned banded floors was built within.

The southern tank was transformed into a new art space. The aspiration of the Art Gallery was to keep the space and structure as intact and 'raw' as possible. Achieving this with minimal strengthening of existing concrete structure, while constructing several levels of new pavilion structures on top of it, was a daunting challenge. The only spatial interventions were a new floor slab over the existing floor, openings cut into the walls for egress, and a circular penetration in the roof slab for a new spiral steel entry stair.

The original tank structure comprises a reinforced raft slab directly on rock, thick lightly reinforced concrete perimeter and dividing walls, slender precast concrete columns over 7m tall with in-situ pedestals and capitals, and a reinforced concrete flat roof slab. The new floor of the gallery immediately above was set above the tank roof slab, to allow a zone for a new steel grillage to transfer loading from the new structures above onto the existing column grid.

Diligent arrangement of the transfer beams maximised the retention of existing columns and fully utilised their existing load capacity. The optimised design only required the replacement of 10 of the existing 125 columns to accommodate the increased loading from the new building above. In these locations, high-strength (100MPa) concrete columns and pedestals were constructed; profiled to closely match the form of the existing columns.

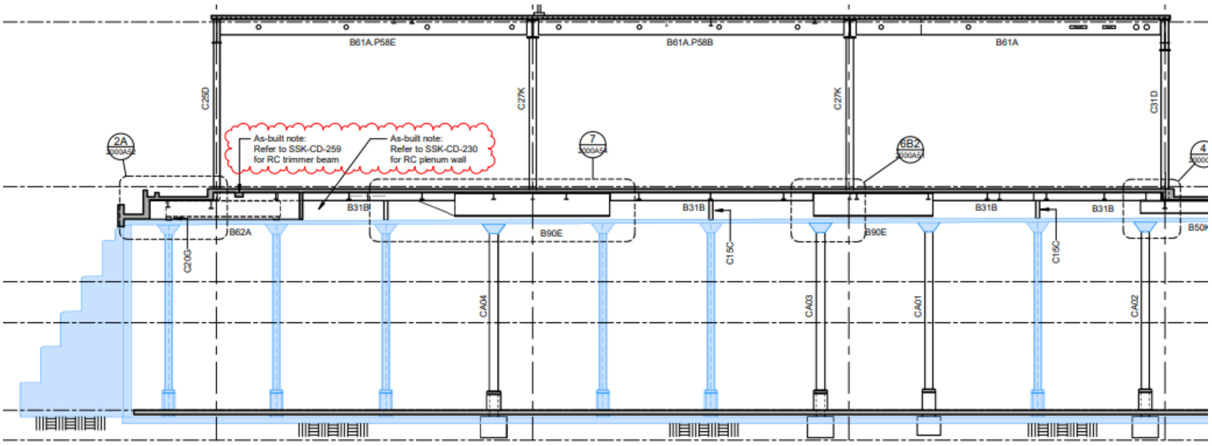

Figure 6 - Section through tank - Existing structure blue, new columns white, transfer floor and new gallery structure over.

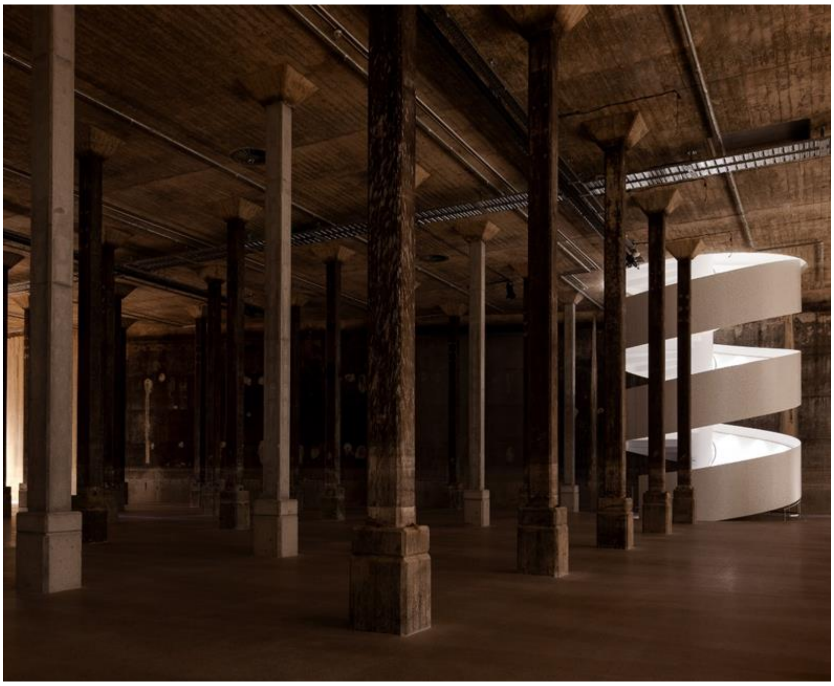

Figure 7 – New columns (lighter grey) among original columns, with new stair. (© Iwan Baan)

The new gallery structure over the tanks was stitched into the tops of the existing walls to take advantage of their lateral capacity, reducing the quantity of new shear walls required at the lower levels.

4 Performance-Based Seismic Design

The ‘Tender’ design of the Sydney Modern structure was based on 2016 version of the National Construction Code (NCC2016) and its referenced structural standards. In 2018, the concrete structures standard went through an extensive revision, with AS3600-2018 superseding the 2009 version. Furthermore, in 2019, the new NCC2019 superseded the 2016 version.

Before the start of construction, Infrastructure NSW requested Arup to assess the impact of updating the structural design of the building for the new NCC and relevant standards. We undertook this study primarily in relation to AS3600-2018, due to the extent of changes in this code, the majority of which relate to seismic criteria, in particular to ductility. We also checked for any ‘flow on’ effects from the seismic design of the concrete structure to the seismic design of structural steel (to AS4100-1998). We also checked the impact of the new composite structures code AS2327-2017 on the design of composite floors and roofs.

In the ‘Tender’ design, the reinforced concrete (RC) stability walls had been designed as “limited ductile” to AS3600-2009, using a conventional response spectrum analysis to AS1170.4-2007. The criteria for limited ductile design became much more onerous in AS3600-2018. The amount of longitudinal reinforcement and extent of wall cross-tying required in walls increased significantly, and rules around aspect ratios were tightened. Many of the walls in the scheme could no longer be considered limited ductile to AS3600-2018 due to their geometry. As a result, for the “deemed to satisfy” design check against AS3600-2018, the original design was considered to be “non-ductile”.

Based on this, our review found that the Tender design did not satisfy AS3600-2018. In order to meet the criteria:

- Reinforcement in stability walls and floor and roof diaphragms would need to be increased by around 60 tonnes overall;
- One key stability wall would need to increase in thickness, and;
- Some vertical steel bracing would need to be increased.

Non-linear Response History Analysis

To seek mitigation of the impact of the code changes, Arup proposed to reassess the structure using a performance-based design approach, using a Non-linear Response History Analysis (NLRHA).

NLRHA is the most rigorous form of analysis used in seismic design. It considers the non-linear behaviour of structural elements under a series of ground motion time histories, applied to the model in X, Y and Z directions. The purpose is to as closely as possible capture the real response of the structure under an earthquake. NLRHA is particularly useful for understanding the seismic behaviour of complex structures for which conventional methods are not well-suited, such as the subject building, which had an inherently complex load path due to its architectural form of interconnected pavilions over several levels.

The use of NLRHA is permitted under AS1170.4, AS3600-2018 and AS4100-2016, however these codes are all limited in their description of application. Where Australian Standards have been limited in procedural information, reference is made to ASCE 41-17, Seismic Evaluation and Retrofit of Existing Buildings.

The ground motions used for the Sydney Modern analysis were based on real recorded earthquakes from around the globe. The ground motions were scaled in both magnitude and spectrum to result in motions that are representative of plausible design level earthquakes for the Sydney region. It is a requirement of ASCE 41-17 that the designer consider 11 ground motions, as this ensures that variations in the ground motion direction and general profile are appropriately considered.

For this assessment, the adopted performance criterion was Life Safety. To demonstrate that life safety to ASCE 41-17 is achieved, plastic strains and rotations less than the Life Safety limit must be demonstrated in 10 of the 11 time histories. Since there is no such criterion in AS1170.4, we adopted a requirement for all 11 ground motions to be within the Life Safety limits.

Target design spectrum

The target design spectrum used in this study was a uniform hazard response spectrum (UHRS) as shown in Figure 8. The design spectrum was derived using a probabilistic seismic hazard analysis (PSHA) in Australia developed by Mote et al (2017) to reflect the location of site, site class and 1/1000 APE along with the consideration of 5% structural damping.

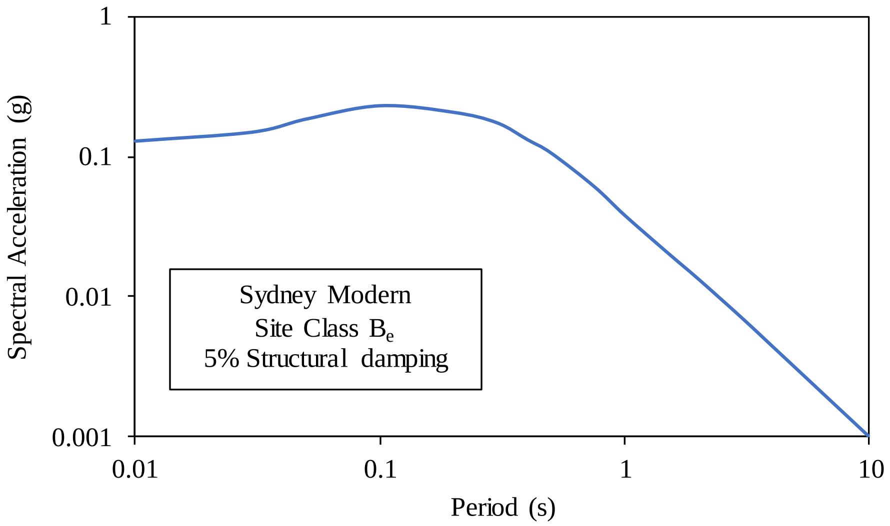

Figure 8 - Uniform hazard response spectrum reflecting location of site, site class, 1/1000 APE and 5% structural damping.

Ground motion selection

The ground motions of controlled magnitude and distance along with the linear scaling factors were obtained from the Pacific Earthquake Engineering Research (PEER) Ground Motion Database (Ancheta et al 2013) [https://ngawest2.berkeley.edu/]. The scale factors of each ground motion were determined using the method of minimise MSE (i.e. minimise the computed weighted mean squared error of record and group average with respect to the target spectrum), as shown in Figure 9.

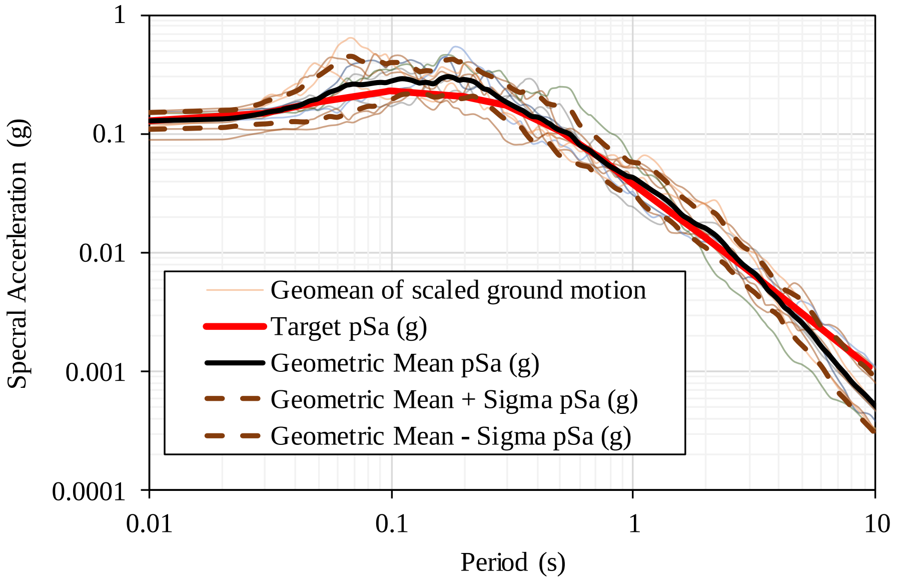

Figure 9: Target spectrum and geomeans of scaled ground motion spectra.

Table 1: Selected ground motions and the corresponding scaling factors

Record Sequence Number	**Mean Squared Error**	**Scale Factor**	**Earthquake Name**	**Year**	**Magnitude**	**Mechanism**	**Distance (km)**
89	0.1188	3.6143	San Fernando	1971	6.61	Reverse	61.75
239	0.1059	0.4103	Mammoth Lakes-03	1980	5.91	strike slip	10.31
403	0.1514	2.656	Coalinga-04	1983	5.18	Reverse	12.53
560	0.1781	2.8697	Chalfant Valley-03	1986	5.65	strike slip	10.69
943	0.2031	2.1935	Northridge-01	1994	6.69	Reverse	65.84
1102	0.0554	0.8753	Kobe Japan	1995	6.9	strike slip	49.91
3220	0.0802	0.6584	Chi-Chi Taiwan-05	1999	6.2	Reverse	41.46
4453	0.4956	2.068	Montenegro Yugoslavia	1979	7.1	Reverse	65.88
5285	0.1031	0.8329	Chuetsu-oki Japan	2007	6.8	Reverse	35.41
6900	0.2483	46.949	Darfield New Zealand	2010	7	strike slip	326.8
8683	0.1029	21.737	40204628	2007	5.45	strike slip	64.06

Modelling of structural elements

NLRHA was undertaken using LS-Dyna software, with elements modelled with either non-linear or linear material properties depending on their criticality and expected behaviour. For example,

- Concrete shear walls (new): Non-linear material model, capable of capturing concrete crushing, concrete cracking and reinforcement yielding. These walls were modelled with additional through thickness integration points, and discrete assignment of material properties to represent concrete layers and the equivalent thickness steel layer. The concrete model selected was a nonlinear model based on EN 1992-1-1, while the steel model was based on EN 1993-1-1. In each case, Australian material properties were adopted, with the material model only providing the response algorithm.

- Concrete shear walls (fuel tanks): Linear material model. (Extent and thickness are such that stresses under seismic actions were expected to be low.)
- Concrete floors: Linear. Seismic stresses were expected to be low (but checked during post-processing).
- Concrete columns: Non-linear, based on the M-N interaction diagram calculated to AS3600 and ASCE 41-17 moment vs. plastic rotation curves. A two-hinge nonlinear beam model was adopted for the numerical implementation. The material model selected has the ability to receive a yield surface based on two tangential M-N diagrams, with a correlation coefficient to inform the biaxial interaction. The nonlinear response in the chosen material model is based on moment versus plastic rotation curves.
- Steel-concrete composite floors: Non-linear; beam sections modelled using section capacities and AS 4100 interaction surface parameters to define yield surface, and metal deck slabs modelled using the same method as the new shear walls.
- Steel framing: Non-linear; similar to beam sections in composite floors, except using member capacity instead of section capacity due to the element effective lengths being greater than that of full lateral restraint. Exception was given for slender members in compression (i.e. very slender columns), where axial member capacity is captured in model, as it is capable of modelling Euler buckling.

When undertaking a NLRHA, expected strengths of materials are used, instead of the lower “characteristic” values used for calculating capacities for design checks on a linear analysis. This means that for the capacities, the mean strength of the material is used. Additionally, the capacity reduction factors (ϕ) are removed from the capacity calculations.

Construction sequencing was taken built into the analysis, to ensure the gravity load distribution in the structure was correct. For example, the analysis took into account the following:

- The concrete structures for the Entry Pavilion and Gallery 1 floors were supported by the Land Bridge which was pre-existing.
- One column between the Gallery 2 roof and the Entry Pavilion roof was to be jacked during construction to remove the deflection of the Gallery 2 roof portal frames under the structural self-weight.

Assessment of structural elements based on NLRHA results

For elements with non-linear materials, the level of plastic deformation from the analysis can be used to directly assess if the structure is adequate and meets the performance requirements in the standards. If reinforcement plastic strains are less than the failure strain, if concrete strains are within the acceptable ranges, and if the steel structure has acceptable plastic rotations, then no design modifications would be required.

Elastically modelled elements and diaphragms need to be checked post-analysis to ensure they carry sufficiently low forces that no plastic deformations or significant change in stiffness.

NLRHA Outcomes

Unlike the “deemed to satisfy” assessment using conventional analysis, the NLRHA demonstrated that the original structural design complied with the seismic requirements of AS3600-2018, with modest additional reinforcement.

In summary:

- Concrete walls: No additional reinforcement was required, nor any increase in wall thickness. The maximum plastic strain in the wall reinforcement was 2.7% (average 2.3%), less than the target strain limit of 5%. The peak compressive stress in the concrete was 47.7 MPa.
- Concrete floors and composite floors: Modest additional reinforcement was required at some collector zones (where floor and roof diaphragms connect to the lateral load resisting system such as concrete walls and braced frames), and a few localised areas.

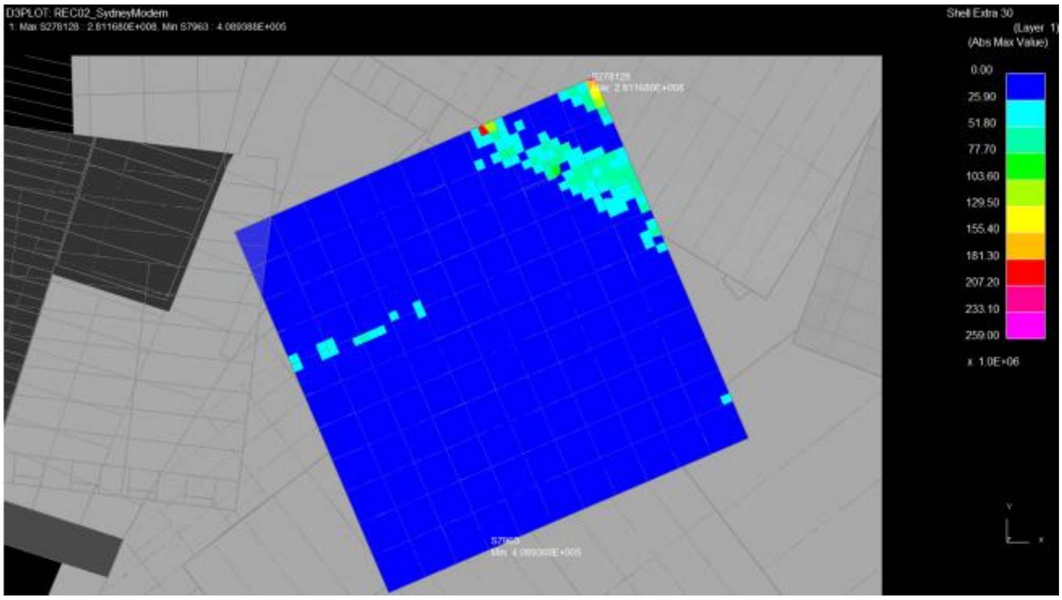

Figure 10: Café Roof Reinforcement (x-direction) Stresses Showing Stress Concentration at connection to Gallery 2 roof

- Steelwork: Minor increase in sizes and connection capacities of a few bracing members, and design updates to a few column base plates.

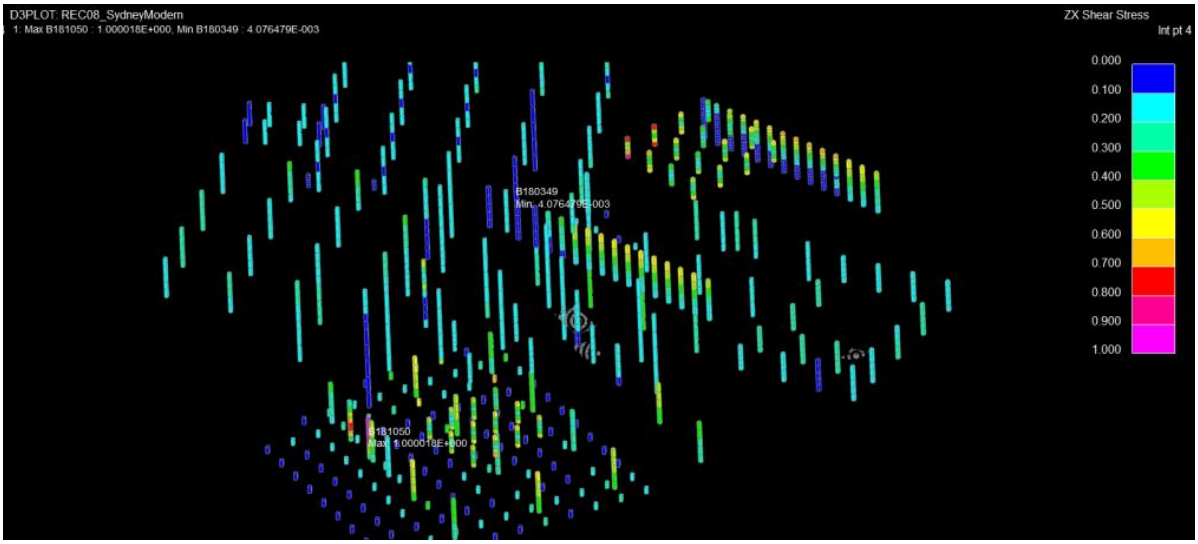

Figure 11: Steel column utilisation plot – Ground Motion Record 8 of 11

The key outcome of the NLRHA was that the additional 60 tonnes of reinforcement that would have resulted from upgrading the design from NCC2016 to 2019 based on conventional analysis was avoided, saving a considerable quantity of embodied carbon and a significant potential cost increase.

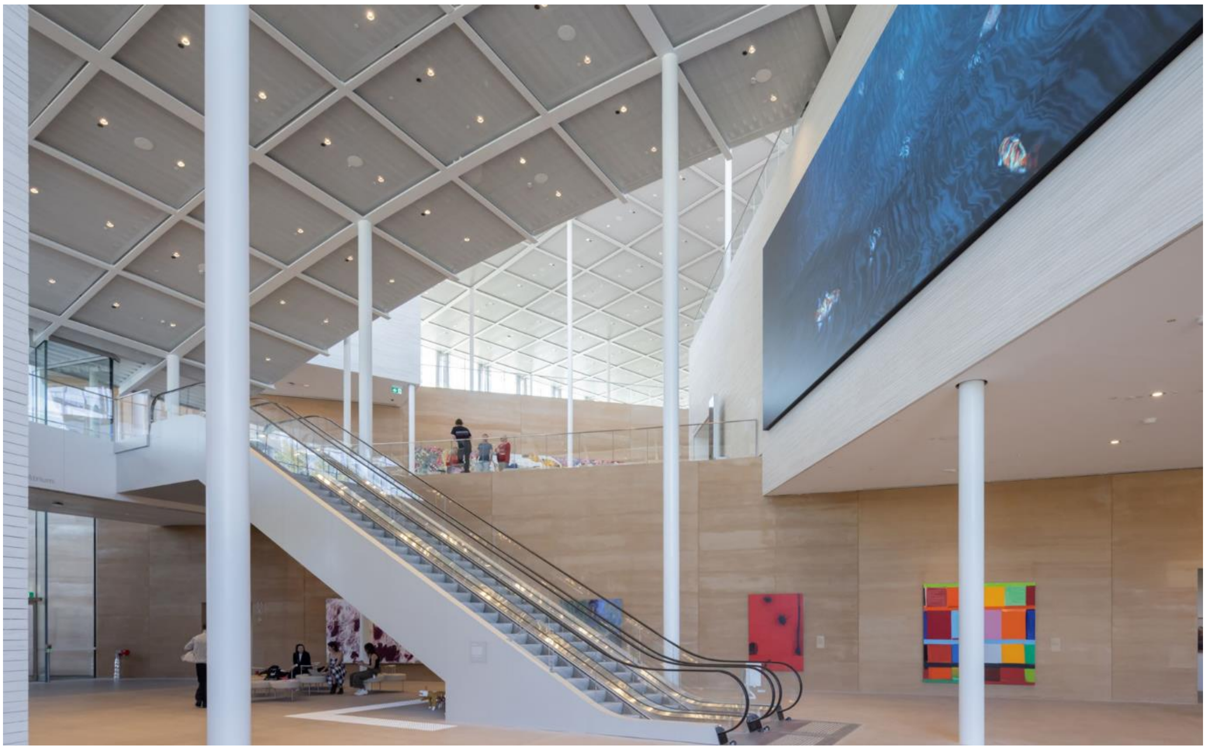

Figure 12: Steel columns and steel-framed roofs, validated and optimised through NLRHA.

By enabling a better understanding of the likely seismic performance of the building than is possible using conventional analysis, the NLRHA provided a robust validation of the stability design, reducing seismic risks to the new building itself, as well as the existing land bridge and fuel tank structures. In particular, the NLRHA validated the design of the slender steel frame of the building's Entry Pavilion, giving the structural engineers confidence that it would work safely as a two-way sway frame with no vertical bracing, while also optimising the sizes of the columns and beams.

References

Timothy D Ancheta, Robert B Darragh, Jonathan P Stewart, Emel Seyhan, Walter J Silva, Brian SJ Chiou, Katie E Wooddell, Robert W Graves, Albert R Kottke, and David M Boore. *Peer NGA-West2 database*, 2013.

TI Mote, ML So, and JW Pappin. "Arup NSHM-Australian National Seismic Hazard Model." *Australian Earthquake Engineering Society 2017 Conference*, 2017.