

## STATE THEATRE CENTRE OF WESTERN AUSTRALIA

REDEFINING STRUCTURAL INNOVATION



**airey taylor consulting**

engineers  
scientists

2011 WA ENGINEERING EXCELLENCE AWARDS  
**CATEGORY: INFRASTRUCTURE AND BUILDING**



### 3. ORIGINALITY AND INGENUITY OF THE SOLUTION



The project requirements and constraints imposed real challenges to the structural resolution of the building. Overcoming these challenges required creativity and lateral thinking to provide a simple yet elegant solution to complex problems. The following are examples of successfully implemented structural solutions:

#### *A. USE OF EXTERNAL CONCRETE RAFTS AND TOP-DOWN CONSTRUCTION TO RESTRAIN THE D-WALLS:*

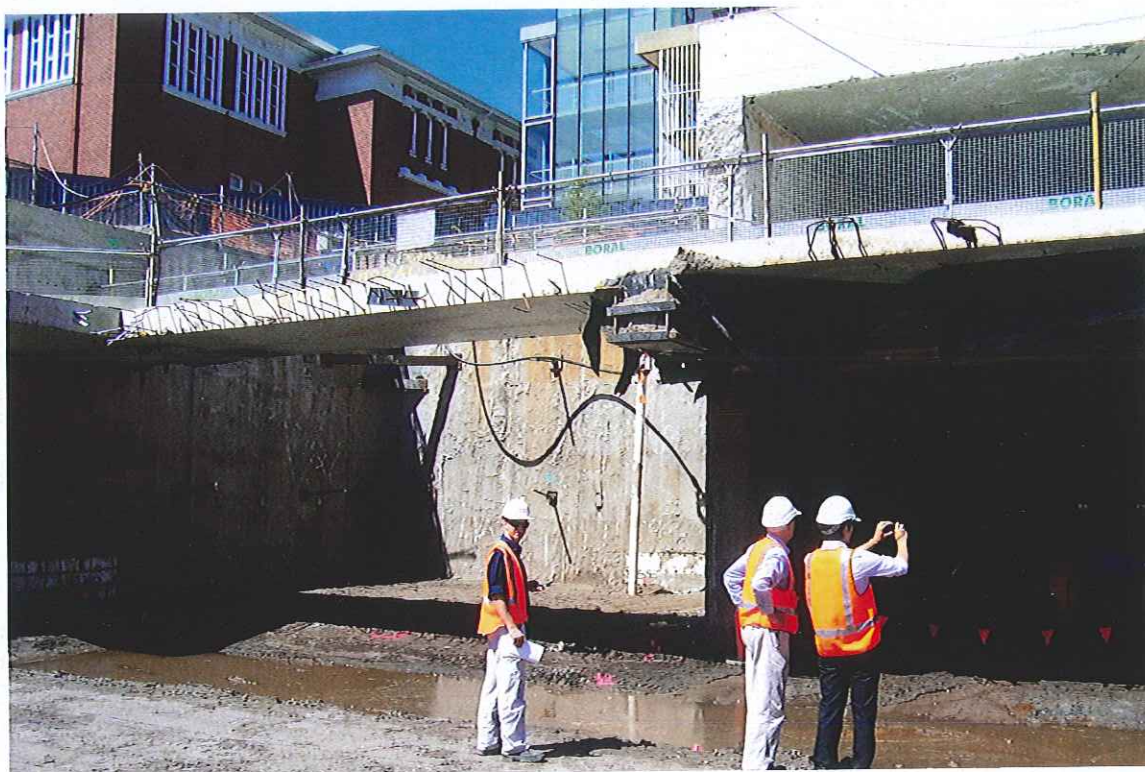
Pre-construction inspections of adjacent heritage-listed buildings that neighbour the intended deep excavation area revealed existing damage to the buildings caused by foundation settlement, and extensive fretting of mortar was present. As these buildings fell within the zone of settlement induced by the deflection of the D-Wall, careful selection of a rigid soil retention system was essential.



The use of permanent anchors for the diaphragm walls was investigated. It was found that they would be expensive and that to gain 100-Year certification, would require accessibility for monitoring and periodic re-tensioning. Accessibility was not achievable within the architectural scheme. Airey Taylor developed the use of top-down construction enhanced with engagement of the wall into the raft (to achieve a full moment resisting connection) to provide the permanent support required.

Due to the isolation requirement, use of internal slabs to restrain the diaphragm was not possible along a major proportion of the D-Wall. Restraint was achieved by casting external rafts that are utilised as foundations to other elements. Multi-level restraint was achievable by engaging two levels of internal slabs or external slab with suspended internal slab. Excavation adjacent to the walls, including under the suspended slab diaphragm, proceeded once the suspended diaphragm slab gained the required structural strength. Temporary anchors were introduced, to the northern wall and lift pit area, and then removed following the full engagement of the walls into the basement's raft slab.





Implementation of this technique successfully achieved the anticipated results. No damage was caused to any of the fragile neighbouring buildings.

#### ***B. SEGMENTED PRE-CAST MULTI-STAGE POST-TENSIONED TRANSFER BEAMS:***

The transfer floor for the main auditorium spans 27.5 meters to bridge over the underground Studio Theatre. The space between the lid of the Studio Theatre and the main auditorium transfer floor created a labyrinth which is utilised by the mechanical engineer to moderate the temperature of the fresh air intake using the thermo-mass. Concrete was the material required to serve this mechanical purpose. The concrete beams that could serve the purpose were too heavy and bulky to be transported and lifted into place. Casting the beams in-situ was not achievable without complicating the construction of the acoustically isolated Studio Theatre.



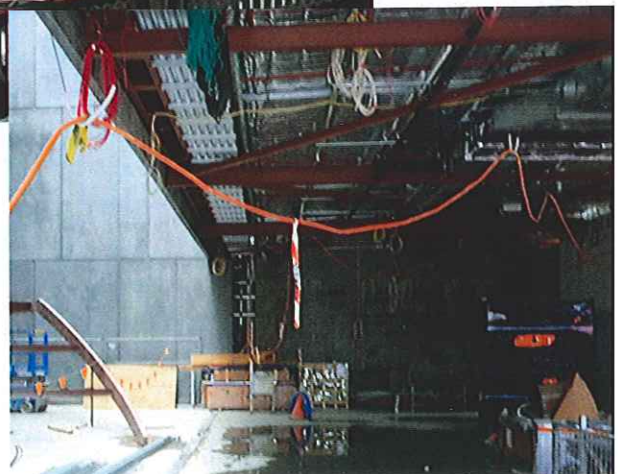




Dividing each beam into three pre-cast segments was assessed as providing a resolution to the limitations of accessibility and lifting capacity. Each transfer beam comprised three pre-cast segments equipped with profiled post-tensioning ducts to facilitate post-tensioning the beams following assembly. Multi-stage post tensioning was required to satisfy the design requirements. The 1st stage post-tensioning was designed to be performed on the assembled beam once the cast in-situ link attained the required strength. The beams were then able to support the loads imposed by casting the transfer floor deck slab. A 2nd stage post-tensioning was applied once the composite beam-slab formation had achieved the required deck slab concrete strength.

### **C. POST-TENSIONED STEEL TRUSS FOR MAIN-FOYER SLOT:**

The formation of a dramatic large span slot in the southern face of the aboveground sound buffer enclosure was an architectural design requirement. In effect, the support structure needed to be capable of spanning the 28m slot which supported three levels of double-face pre-cast concrete clad panels within inducing misalignment of the panels.





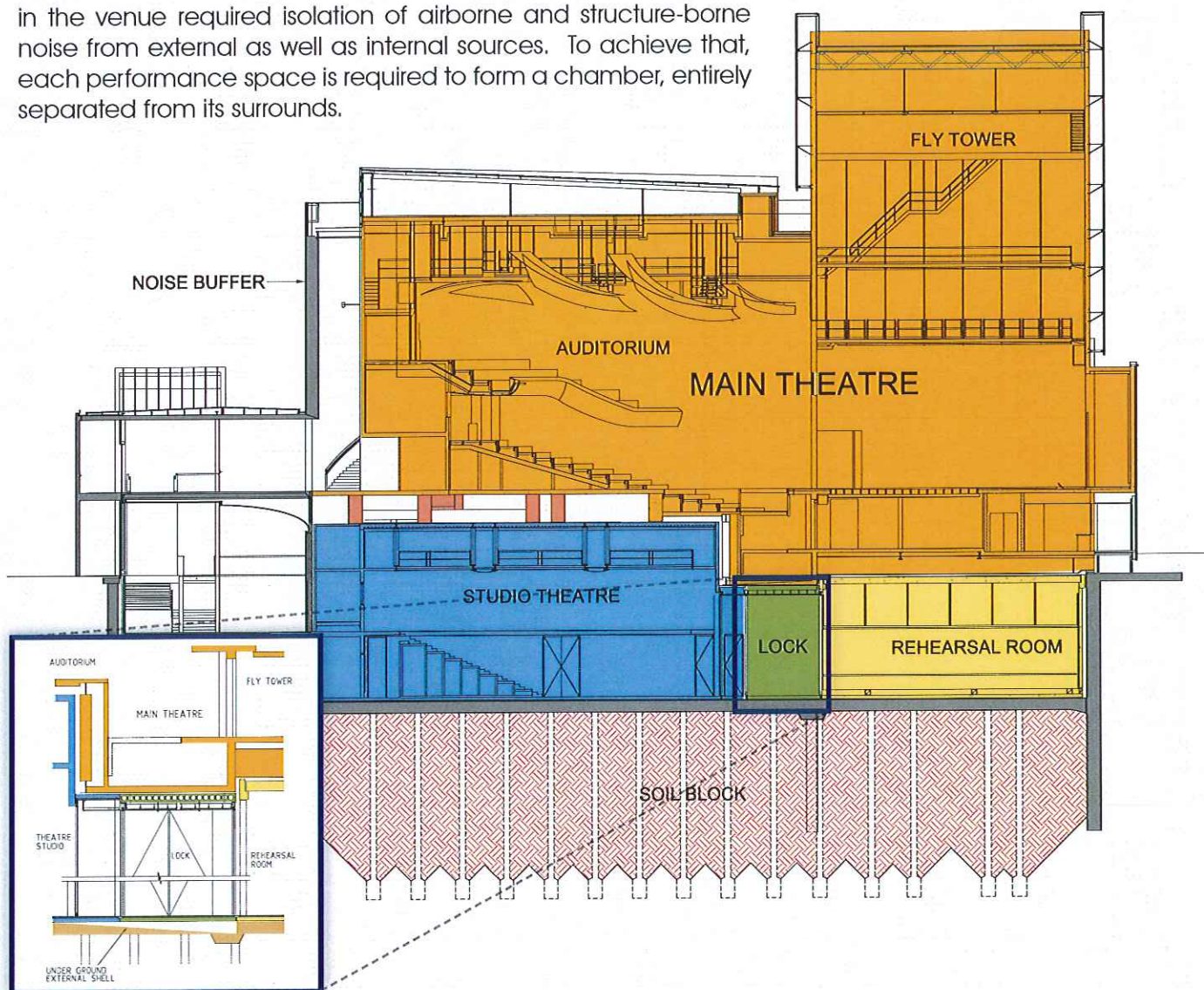
## 2. USE OF SOUND ENGINEERING PRACTICES AND PRINCIPLES

The structural design process commenced with analysis of the design brief, concept architectural design documents and the building site. The analysis identified number of critical project requirements and design constraints that needed to be properly addressed at the schematic design stage to achieve a successful outcome. These included:



- Acoustic isolation between the multiple function areas;
- Deep excavations close to heritage buildings;
- Design against buoyancy/uplift;
- Limited plot area and restricted site access;
- Restricted crane lifting capacity due to site constraints;
- Watertightness and vapour transfer limitations;
- 100 year design life.

In what is a very busy urban environment, achieving optimum acoustic isolation between the various performance spaces in the venue required isolation of airborne and structure-borne noise from external as well as internal sources. To achieve that, each performance space is required to form a chamber, entirely separated from its surrounds.



This translated into a structural concept comprising an external underground watertight shell to house the underground performance spaces to isolate them from ground-borne noise. The aboveground performance spaces were stacked over the underground performance spaces. Acoustically isolated bridges were used to support the aboveground performance space. The Main Theatre was cocooned with an external shell to buffer against airborne noises. The structural concept was adopted by the architect and acoustic consultant.





Deep excavation required the use of a high rigidity soil retention system that could be installed with minimum vibration to prevent disturbing the relatively loose soil under the neighbouring vulnerable heritage-listed buildings. A soil retention system comprising diaphragm walls for the deep excavation and secant pile walls for the shallower excavation, offered the best, most cost effective retention system.

Although cantilevered walls for the shallower excavations provided adequate rigidity, this was not adopted for deeper excavation where permanent propping was essential. Use of permanent ground anchors was investigated and found to be prohibitively expensive and technically unachievable for the stated design life. Instead, top-down construction technique was selected to provide the lateral restraint to the deep-excavation walls.



Diaphragm and secant-pile walls made with Self Consolidating Concrete (SCC) with pore blocking additives were selected and designed to form the soil retention system and installed deep enough to cut the high permeability soil strata to reduce the environmental impact.

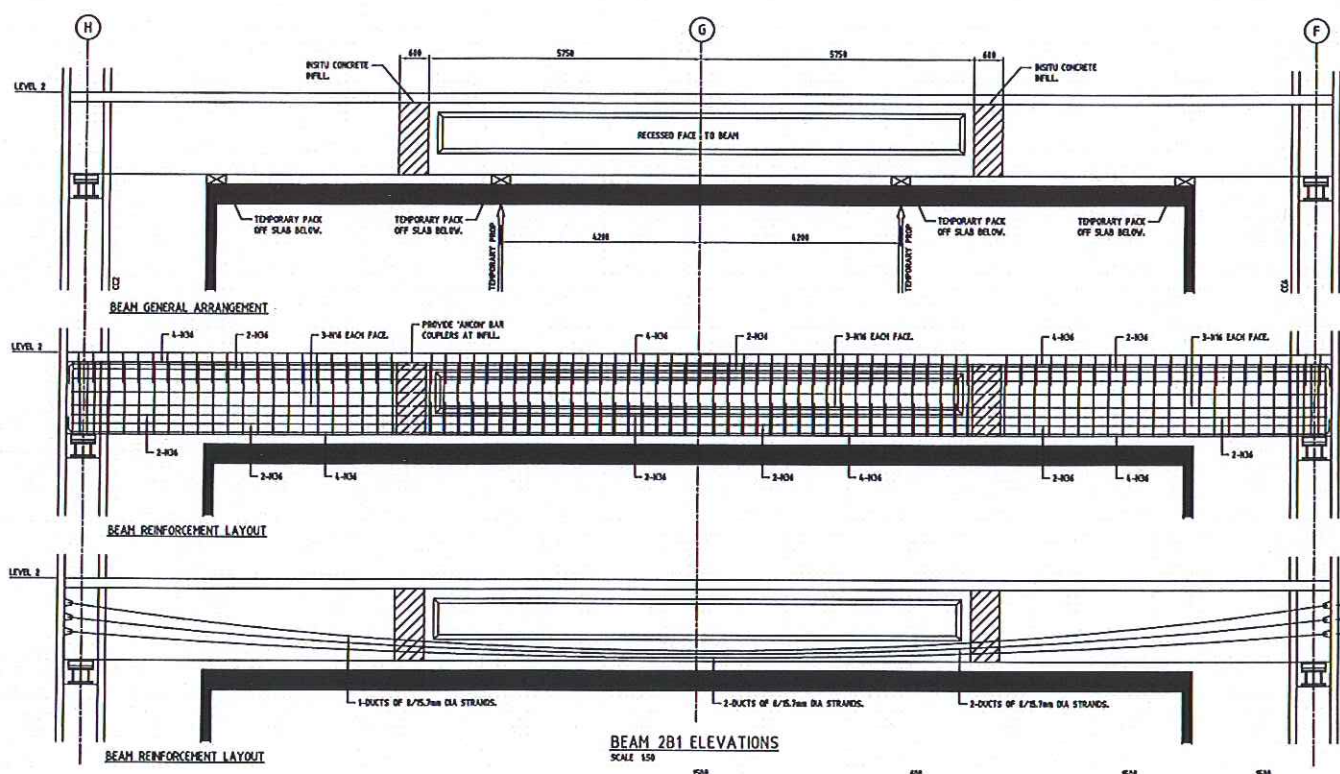
To mitigate constraints imposed by limited plot area, Airey Taylor proposed to the design team that splitting of the construction into Forward Works phase and Main Contract Phase would enhance early project delivery and prevent large size machinery and equipment crowding the site. The letting of the Forward Works Contract during the Design Phase imposed a discipline on the architectural and structural systems, potentially facilitating early project delivery.





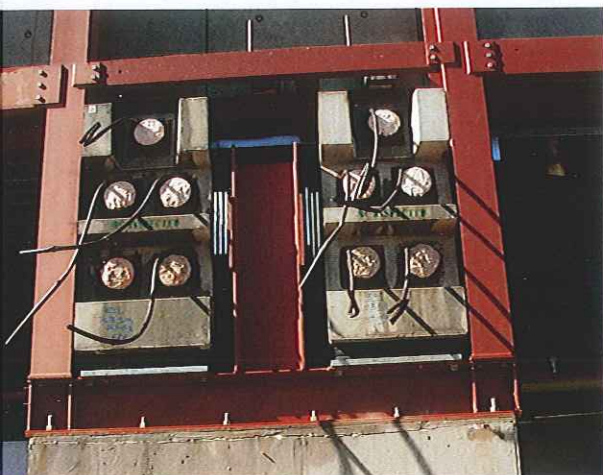
The base of the underground external shell was required to resist high net uplift pressure, and anchoring of the base into the ground was needed. Conventional permanent anchors were discarded due to unavailability of access for monitoring and re-stressing. Instead, engagement of the soil mass and locking the mass into the base to form the counterweight to the buoyancy forces was achieved through the use of P/T belled-end piles, a novelty designed for this project, as discussed in (7) of this submission.

The architectural configuration of the upper building was locked into the surrounds, which imposed height restrictions. Minimising the space allocated to house the bridging beams over the underground performance spaces was essential to minimise the depth of the underground portion. Using 1m deep steel beams to span the 15 meters over the Rehearsal-Room 1 underground enclosure was possible using the composite action of the under-stage concrete deck. Using profiled composite decking and pre-cast hollow-core concrete planks to form the under-stage floor facilitated prop-free construction of the transfer and allowed maintenance of the acoustic separation from the RR1 enclosure. The Fly-Tower concrete walls were designed as deep beams, locked into the Main Stage transfer structure and supported on discrete acoustic bearing pads directly on the diaphragm walls of the underground external shell to satisfy the acoustic isolation.



Multi-stage prestressing was used to post-tension the transfer beams, forming the Main Auditorium base, thereby engaging the theatre's concrete horseshoe shell into the transfer slab. This formed a deep cross-transfer structure capable of distributing the load of the large-span auditorium roof onto the transfer beams and forcing compatible movement between the transfer beams.





The external enclosure of the Main Theatre consisted of internal and external architectural pre-cast panels. To support the architectural cladding, steel structure was utilised to transfer the panel weight back to the external underground shell and provide vertically spanning propped cantilever action capable of resisting the design lateral forces. To satisfy the acoustic isolation requirements, acoustically isolated pads were used to engage the cantilever props to the stage's horseshoe shell.

Maximisation of offsite production was essential to resolve the constraints generated by the size of the site and the high percentage of built-up area. Delivery sizes had to be limited due to road and site accessibility constraints; factors which were included in the material selection for the structural system. The structural design incorporated steel, conventional RC, post-tensioned concrete, pre and/or post-tensioned precast concrete, reinforced and un-reinforced masonry, structural glass, timber, composite construction and post-tensioned steel. Comprehensive computer modelling was used to analyse the complex configurations and interactions. All design was performed to the relevant Australian Standards, following review of literature and application of high level engineering judgment, based on a wealth of experience, including that of associated technology leaders and specialist Contractors.





## EXECUTIVE SUMMARY

The State Theatre Centre of WA (STCWA) is a recently completed, world class venue for performing arts, located at a prominent corner of the Perth Cultural Centre, home to the Art Gallery of Western Australia, the WA Museum, the State Library, the Perth Institute of Contemporary Arts, Arts House and several other culture and arts organisations.

The \$91 million (including the Theatre Equipment cost) project delivered a 575-seat Main Theatre, a 237-seat flexible Studio space, two Rehearsal Rooms, outdoor performance space and spacious foyers and public amenities.

The requirements of the project were rigorous from the outset: venue location, size of plot, aesthetic appeal aspects, acoustic isolation of performing areas and practice rooms, complementary height with surrounding properties, confined access and high volume traffic density surrounding the proposed location in the Northbridge area.

To address site constraints, the architectural design, winner of the international design competition CentreStage, provided a concept that;

- Located the Main Theatre on top of the Studio Theatre and vertically stacked the foyers that directly connect to Roe, William and James Streets through the public concourse level.
- Submerged large portions of the building for economy of footprint. This approach ensured negligible impact to the low-rise Northbridge building surrounds, and effectively engaged the adjoining heritage listed buildings. The high water table level in the reclaimed Lake Kingsford site selected as the venue meant that the building is subject to more than 60kPa design uplift pressure (85kPa at the lift pit area). Essentially, the underground shell is an "anchored boat".
- Acoustically isolated each of the main functional spaces from their surrounds. Acoustically isolated compartments within the structural shell had to be developed, with each compartment unable to share common members. Full shell compartments comprising base, walls and lid supported upon acoustic pads creating totally independent structural enclosures floating in isolation inside the external sound buffer enclosure were designed.
- The design had to limit the environmental impact of dewatering and excavating the Potential Acid Sulphate Soils (PASS) of the site.
- Met the Client's stated criteria of 100 year design life of the building, with minimum recurrent maintenance

More than 70 specialists were involved during the planning, design and construction stages. Airey Taylor Consulting are proud to have provided the Structural and Civil design and have been an integral part of the team that provided the Client, and the people of Western Australia a state of the art Performing Arts Centre, which complements and revitalizes the Perth Cultural Centre with an innovative and elegant design solution.



## CATEGORISATION STATEMENT

Airey Taylor Consulting are a small, multi-disciplinary Engineering and Scientific practice located in West Perth.

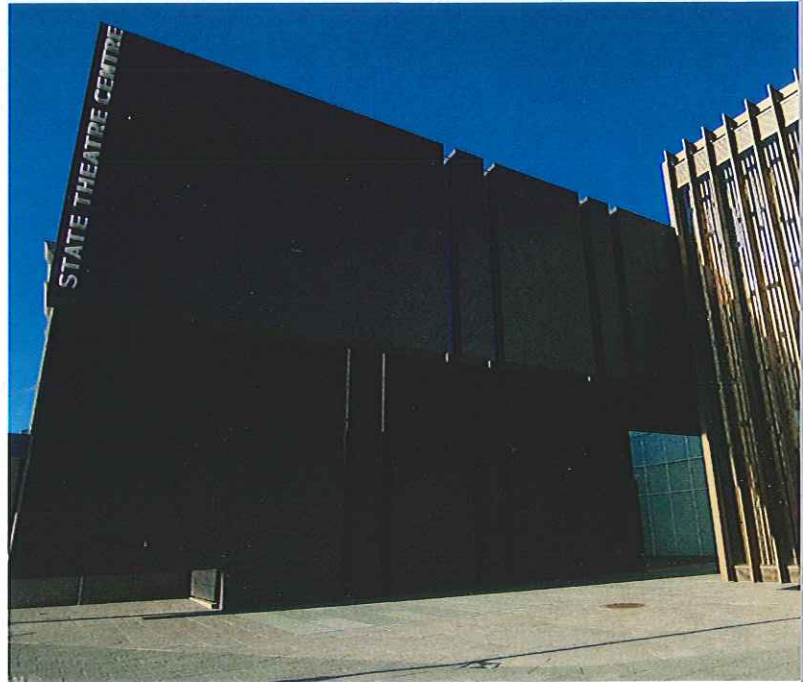


The organisation has strong longevity in structural design and lays claim to some 30 000 projects since its inception. At the time of commissioning, Airey Taylor Consulting staff comprised 4 Structural Engineers, 1 Civil Engineer, 1 Scientist and 4 Draftspersons. We currently have 7 Structural Engineers, 1 Civil Engineer, 1 Scientist, 7 Draftspersons, 1 Engineering Inspector and 3 Administration staff.

Airey Taylor were recommended by the Department of Culture and the Arts as Sub-Consultants to Kerry Hill Architects, for their innovative and unique approach to solving the complexities imposed by the competing needs of functional requirements and site constraints on the project.

The design called for a 100 year public facility, providing a world-class facility for Western Australia's Performing Arts. The Centre demanded durability, functionality, innovation, and aesthetic elegance that mirror the Performing Arts sector.

Airey Taylor Consulting are proud to have delivered just such a facility for the client, Theatre users, and the public of Western Australia. It is indeed a facility to be justifiably proud of.





# SUBMISSION

## 1. ATTENTION TO OCCUPATIONAL HEALTH AND SAFETY



Planning of the construction techniques and material selection for the different structural elements was performed at the early phase of the schematic design stage in close liaison with the Construction Consultant. Review and analysis of OH&S risks involved in the selected construction technique and sequence, preceded adoption of the most appropriate selection.

A large part of the building is positioned underground. Deep excavation next to heritage listed buildings had to be undertaken. Due to the presence of Potential Acid Sulphate Soils (PASS) in the site, measures to reduce the dewatering operations to reduce the soil aeration and acidification were assessed as essential. Diaphragm walls were selected as the soil retention system, and constructed deep enough to cut the high permeability soil strata to effectively reduce water seepage into the basement hole during excavation, reducing the dewatering need and the environmental impact, as well as reducing the OH&S issues associated with the excavation of acidified soils.

The selection of the top-down construction technique to prop the Diaphragm walls prior to excavation minimised the lateral deflection of the D-walls. Thus this technique prevented soil settlement under the footings of the adjoining heritage buildings and maintained the stability of the vulnerable walls, minimising risk.

Attention was paid in detailing the structure to ensure the stability of the structural elements during the erection and reducing construction risks. This included minimisation of the need for formwork and scaffolding.

Attention to OH&S extended beyond the construction period towards achieving a healthy environment. To this end, prevention of vapour ingress into the basement through the concrete walls was considered a design objective in reducing the risk of fungal growth in timber and fabric finishes. Special concrete mixes were specified and produced, with the use of pore blocker, successfully achieved the objective.

The design of the acoustic floating floors included provision for wheel loads of high load intensity to facilitate the use of vertical mast working platforms. This was selected to achieve high OH&S standards during the operational maintenance of the venue.



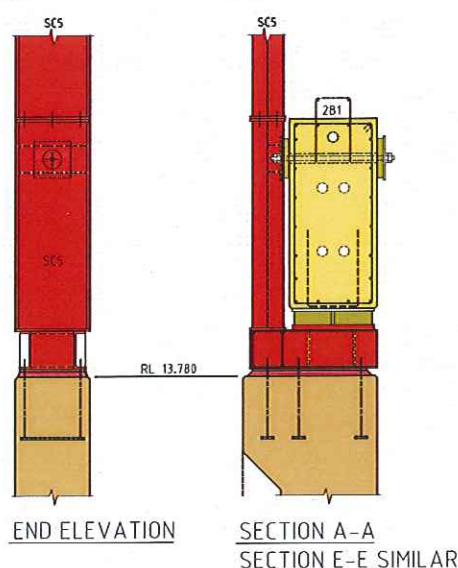




Instead of using a heavy, large excessively rigid support structure, a much lighter post tensioned steel structure was designed and documented to satisfy the requirement. The design comprised a 4m deep pre-fabricated segmented steel truss (to facilitate transport and erection) assembled on site on two temporary supports to change the truss configuration from 28m single span to a three-span continuous truss. The steel trusses are provided with paths to feed two Macalloy stress-bars. Each stress bar runs diagonally in the truss to connect between the central 1/3rd section of the lower-chord and the columns top ends. The principle of the design is to shorten the span to create the required rigidity for successful cladding and perform the full cladding. Following the completion of the cladding, the Macalloy bars were stressed to create upward forces in the stress bars sufficient to fully release the temporary columns of their loads and transfer their load onto the top of the end columns through a deeper triangular truss formation. The design was implemented, and the intended outcome achieved.

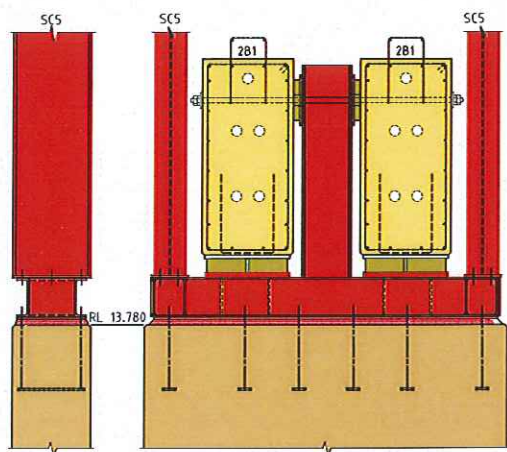
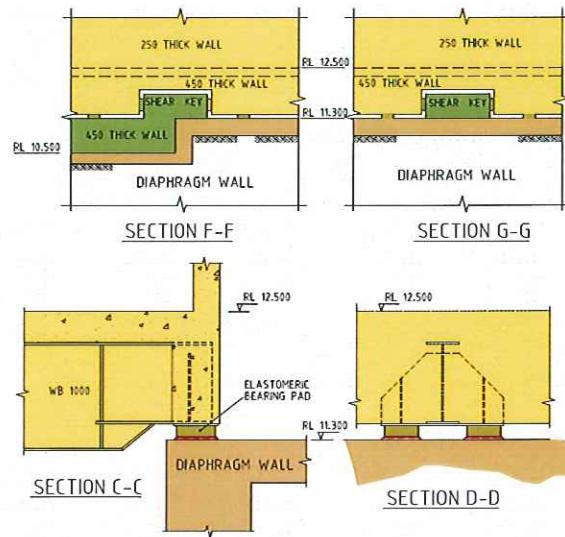
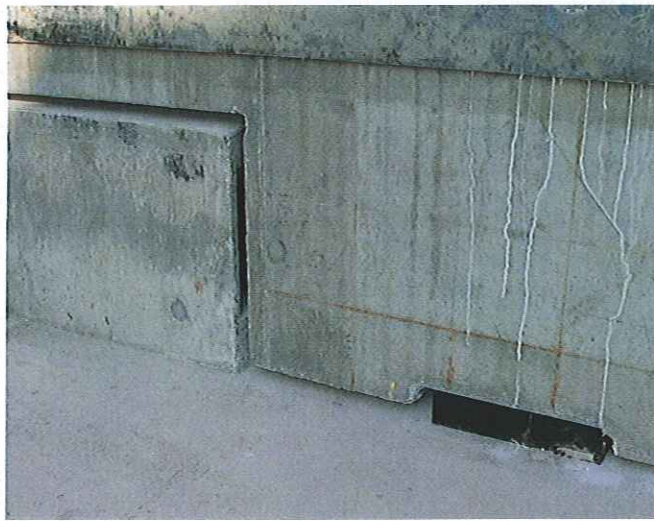
#### ***D. USE OF SHEAR KEYS TO RESTRAIN THE ABOVEGROUND THEATRE MOVEMENT UNDER SEISMIC SHAKE:***

One of the design challenges imposed by the acoustic isolation of the aboveground Main Theatre was to devise an effective restraint of the structure against seismic shake while seating the structure on relatively soft acoustic isolation pads. A special seating design for the auditorium's transfer beams with a protruding shear key was developed. In addition, two reinforced concrete blocks were designed to protrude from the top of the D-walls to act as shear keys and lock the shell of the floating Fly Tower structure to the underground exterior shell. All shear keys were connected to the floating structure through vertically positioned acoustic pads to maintain effective acoustic isolation.

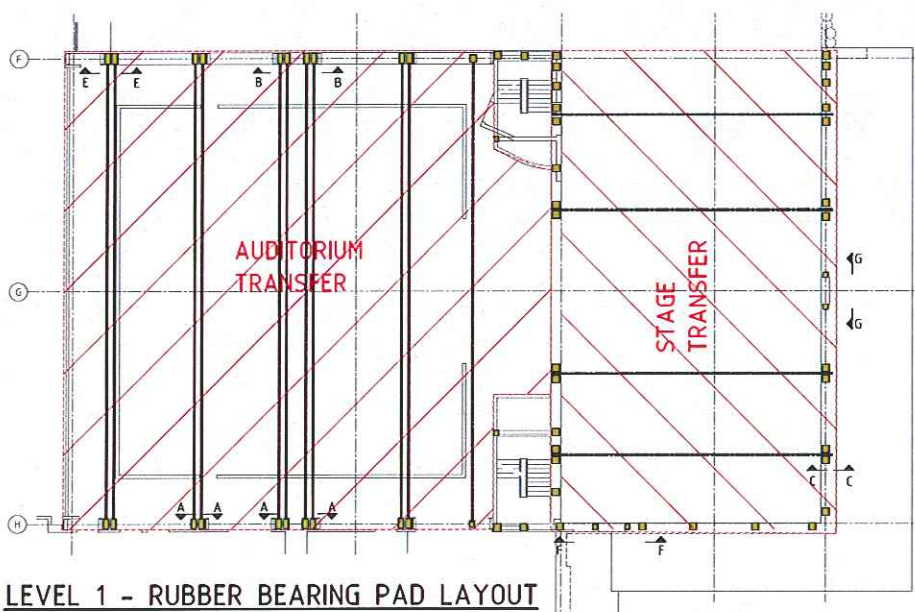




Examples of the implementation of the special seating design for the Main Theatre's transfer beams with a protruding shear key.



END ELEVATION  
LEVEL 1 - RUBBER BEARING PAD DETAILS



LEVEL 1 - RUBBER BEARING PAD LAYOUT



#### 4. BENEFITS TO THE COMMUNITY

The STCWA complements the Perth Cultural Centre and effectively participates in creating the dynamic hub that stimulates the city. The Centre provides a suitable venue to gather major cultural institutions, arts companies and individual artists and attracts a large and diverse group of people who want to make connection with each other or with arts and cultural experiences.

The prevention of damage to the adjoining vulnerable heritage listed buildings, through the employment of the top-down construction technique, facilitated the revitalization and utilization of these buildings as part of the venue, thus maintaining their heritage and commercial value.



Successful optimisation of the structural component, reduction in the scaffolding needs, and the development of a durable design that requires minimum maintenance, has cut the capital and running cost of the venue.



The utilization of the sophisticated techniques has provided a fertile ground for developing and advancing the knowledge, expertise and lateral thinking of all those who were privileged to be involved in designing, detailing and/or construction of this outstanding structure.





## 5. CONTRIBUTION TO SUSTAINABLE DEVELOPMENT



Limiting dewatering of the site and aeration of the PASS soils was set by Airey Taylor as a design objective to limit environmental impact. Extending the D-walls into a lower permeability soil stratum limited the dewatering to inside the box formed by the D-walls. De-watering was always maintained 300-500mm below the excavation level to minimise environmental impact.

Engagement of the retaining walls into the lower raft and the distribution of small size post-tensioned belled piles resulted in design optimisation of the system. This ensures the raft thickness was limited to 600mm with low reinforcement ratio. The design stresses under the action of the 60kPa uplift pressure were successfully maintained below the tensile strength of the plain concrete through the effective distribution of the piles and the full engagement of the raft into the D-walls.

Conventional reliance on waterproofing membranes was abandoned in waterproofing the walls and basement slabs. Instead, pore blockers were used in the concrete for the retaining walls and rafts to provide the water and vapour barrier.

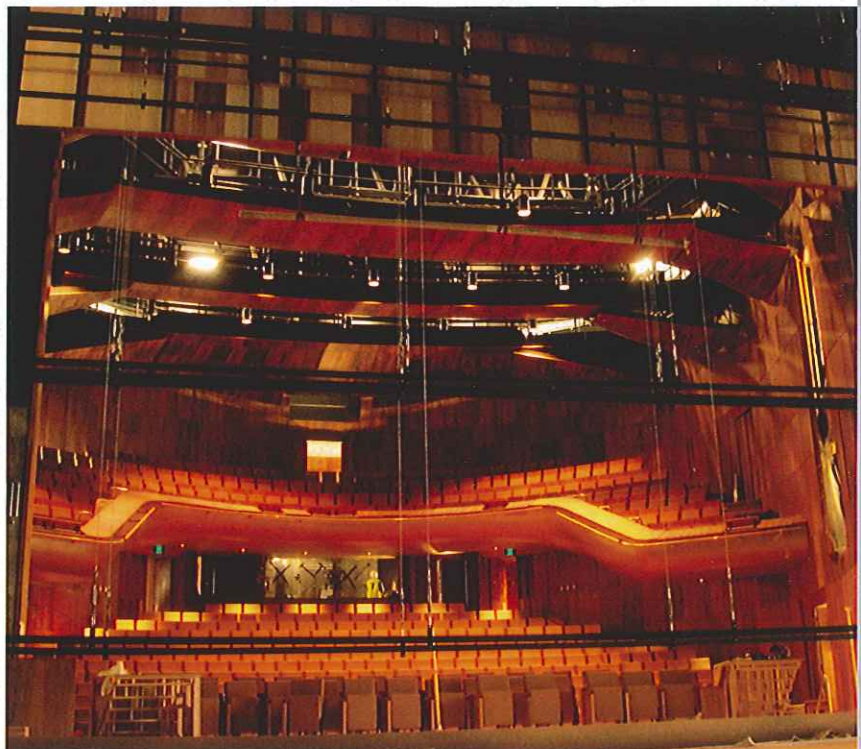
Shaping of the exposed steel structural elements into forms and aspect ratios to suit the architectural visual requirements resulted in effective reduction in the use of finishing material, thus reducing total project cost and facilitating low-cost maintenance of the structural elements.

Reduction of the volume of concrete and formwork transported and consumed in the project was achieved through the following:

- a) The use of hollow-core precast prestressed panels in constructing the 7m high walls for the Rehearsal Room and the Studio Theatre corridors;
- b) The use of AFS LOGICWALL to form the concrete walls;
- c) The maximisation of the use of hollow-core precast prestressed planks in constructing the concrete floors;
- d) The effective use of composite steel formwork systems.

Structural timber was used extensively in the main auditorium to reduce total weight applied on the large-span transfer floor, and to achieve superior sound absorption quality. This added substantial value to the quality of sound within the performance space.

At the Bronze Box, aluminium louvres were designed to stiffen the glass panels and achieve minimisation of structural glass thickness, in addition to providing their principle function. The same applied to the Foyer and Main Bar floor, where FIELDERS CF210 deep deck profiles were laid on top of a thin composite steel deck to provide permanent formwork for the one-way Post Tensioned structural ribs that form the slab. Utilising the ribs dead formwork as A/C air distribution ducts, increased the use of thermo-mass, while reducing concrete and construction formwork.





## 6. SIGNIFICANCE OF THE WORK AS A BENCHMARK OF AUSTRALIAN ENGINEERING



From the outset, the project has held a high profile. From the thirty year gestation period where stakeholder consultation occurred, to the international Architectural competition for concept design (CentreStage), to the choice of location and deliberately innovative means to deliver requirements, the project has been in the public gaze.

The project represents a singularly unique design in Western Australia. Sponsored and supported by successive governments, and designed to showcase Western Australian design, construction and arts innovation, the projects has delivered quality.

There has been much interest in the Architectural, Structural and Construction design and implementation, from professionals and public alike.

**Ministerial Media Statements:** Hon Sheila McHale 14/12/2006, Hon John Day 27/01/11

**Seminars...** Engineers Australia New Performing Arts Venue 18/11/2008

**Blogs...** Complete/State Theatre Centre of Western Australia 15/12/2008

**Websites...** Department of Culture and the Arts StageOneVision portal

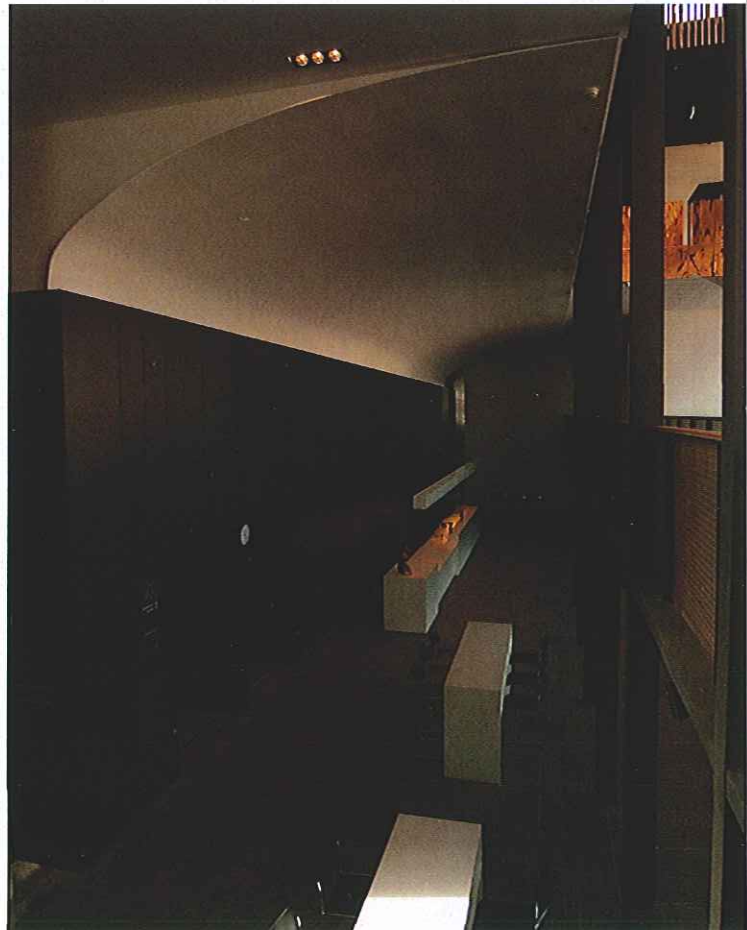
**Magazines...** Frame Magazine 12/04/11,

**Newspapers...** The West 14/10/11, 28/01/11, Herald Sun 28/01/11, The Australian 12/04/11

**Television...** ABC News, Channel 7 News, Channel 9 News, Channel 10 News of 27/01/11

By use of a combination of ingenuity, novel approaches, and leading edge techniques, the significant site and client requirements of the project were able to be structurally creatively attended to, with a variety of resolutions. Examples of a number of intriguing structural solutions designed and successfully adopted are discussed through this submission.

Airey Taylor Consulting has had a long history of advanced, innovative and open-minded approaches to such projects. While remaining at all times client focussed, Airey Taylor Consulting is adept at providing elegant structural resolutions which are appropriate to the requirements of each project. In the STCWA, peer agreement and recognition of the achievement has been freely given.

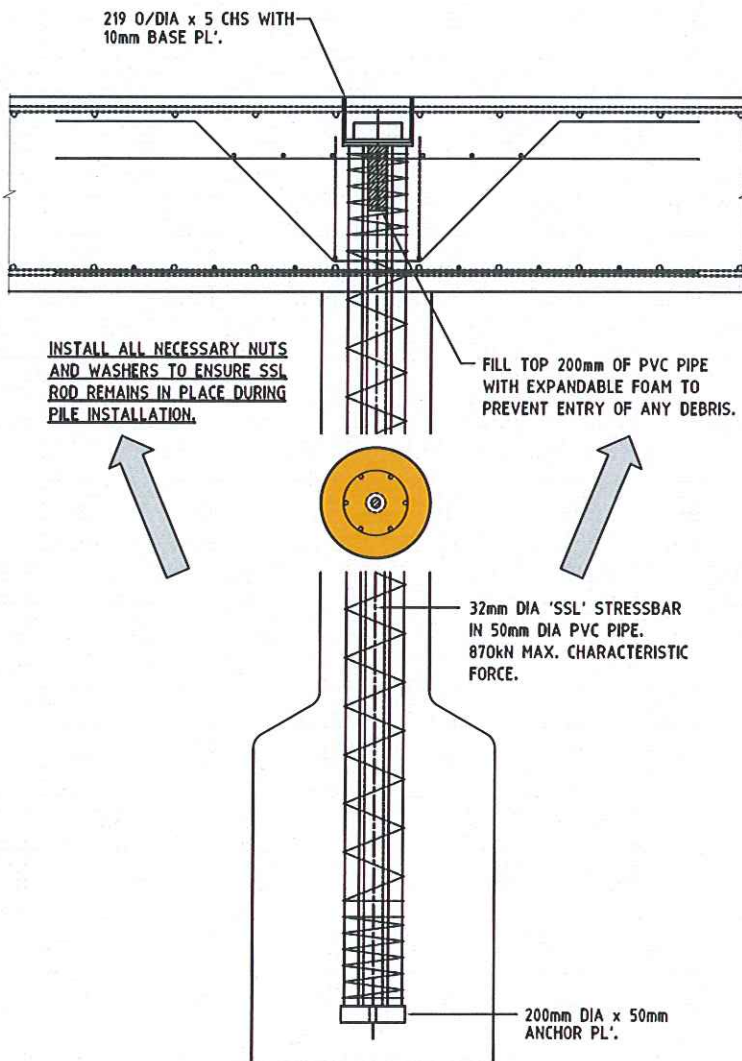




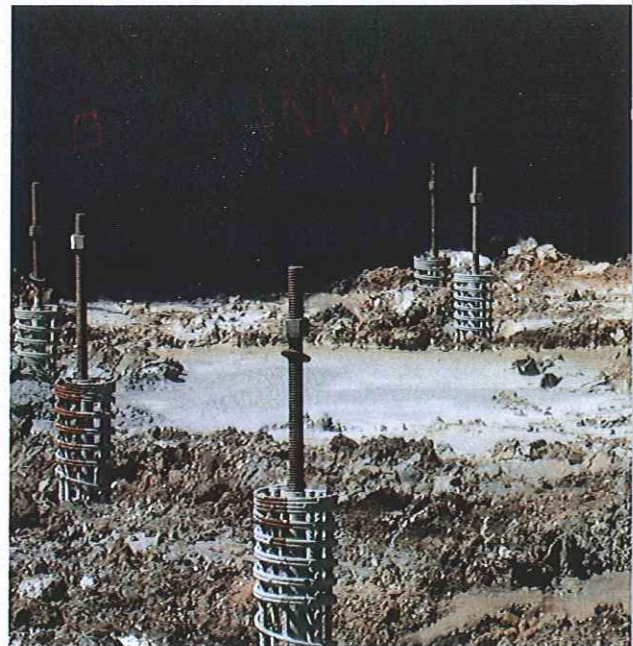
## 7. USE AND DEVELOPMENT OF INNOVATIVE DESIGN



The development of the small diameter P/T belled-end pile is a novel design to engage the soil mass and provide the buoyancy resistance required. The principle is to generate compressive stress in the pile shaft high enough to force upward movement of the belled-end through elastic shortening of the shaft in the dense soil. With small movements, significant soil bearing pressure will develop at the top surface of the belled-end of the pile. The upward movement of the belled-end of the pile causes part of the post-tensioning force to engage the soil mass while the balance of the force creates a permanent compression field in the pile shaft. The soil shaft engaged provides the buoyancy resistance, while the permanent compression in the shaft mitigates concrete cracking, thus maximising the corrosion protection to the P/T pile.

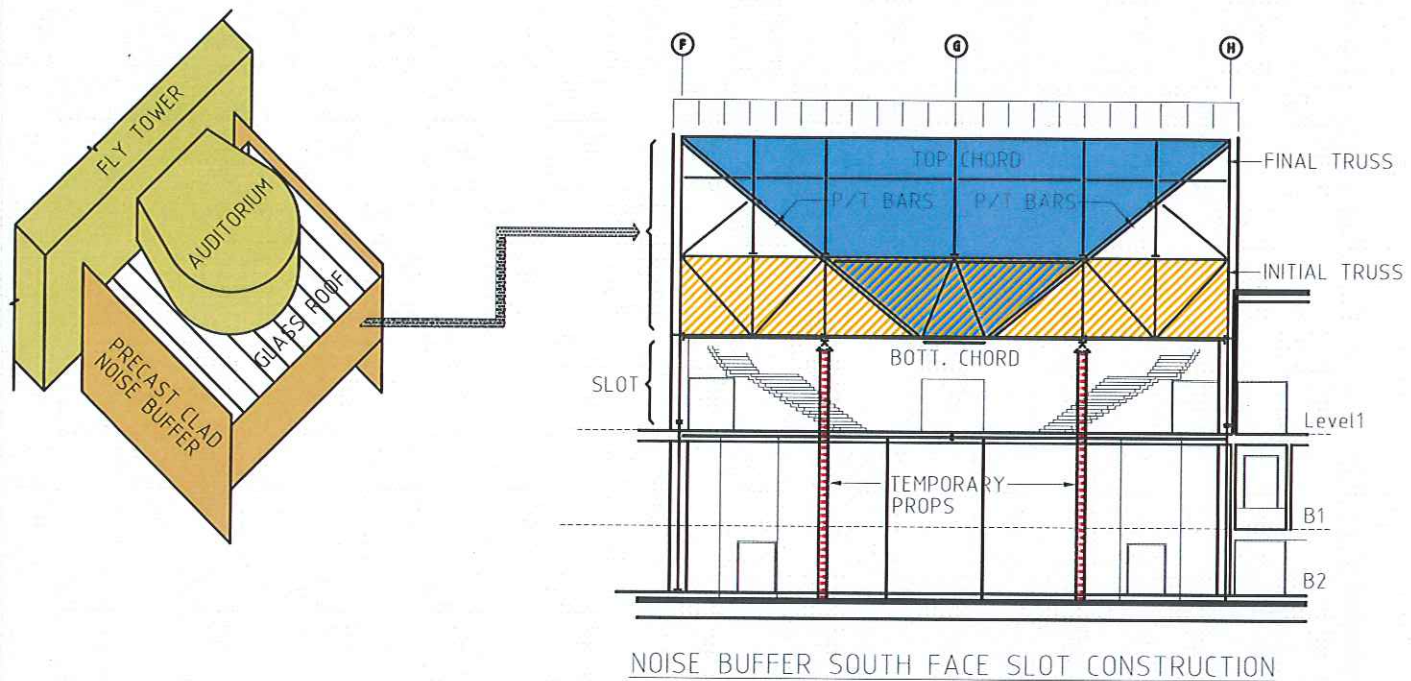


TENSION PILE DETAILS

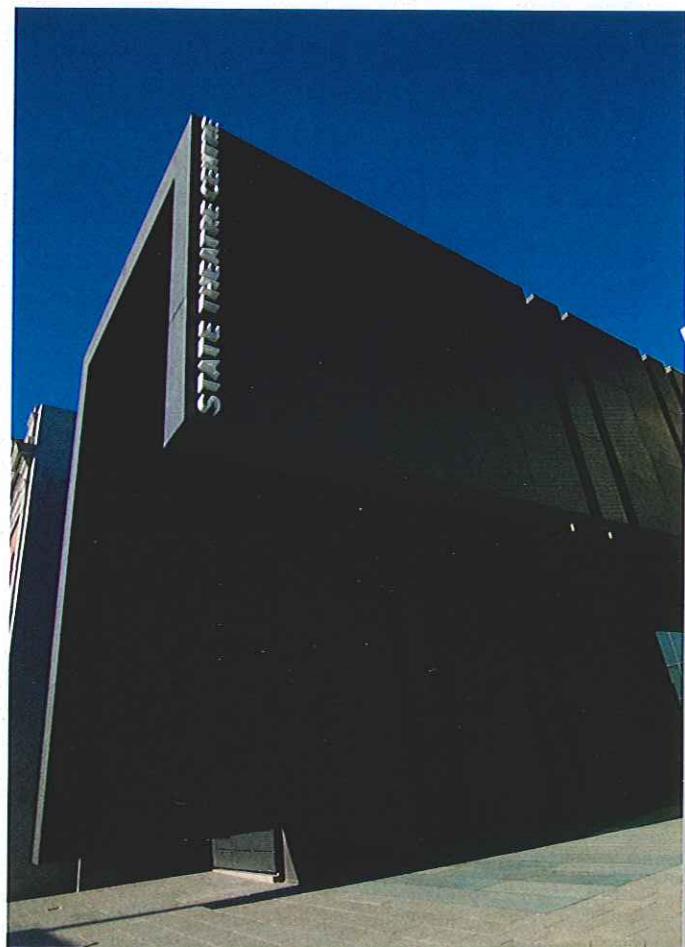




The inventive use of the post-tensioned steel truss discussed in 3.c is another example of creative design.



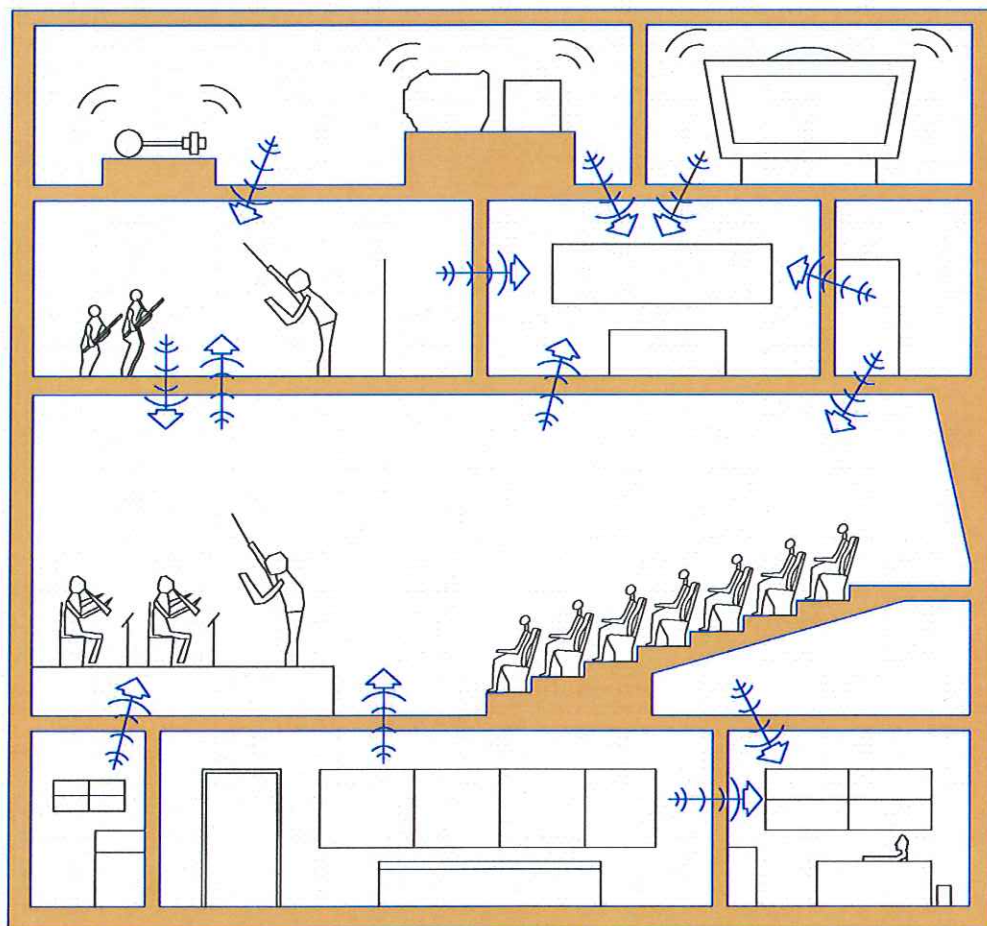
The Entry Canopy at William Street entrance presented a special challenge. The eccentricity between the centre of mass and centre of rigidity causes the canopy structure to want to twist. The creative structural resolution in this case involved creating an internal force in the canopy structure forcing an opposing twist. Controlled internal forces were able to be imposed by devising specially arranged adjustable roof rod-bracing. This solution was implemented and the intended outcome was successfully achieved.



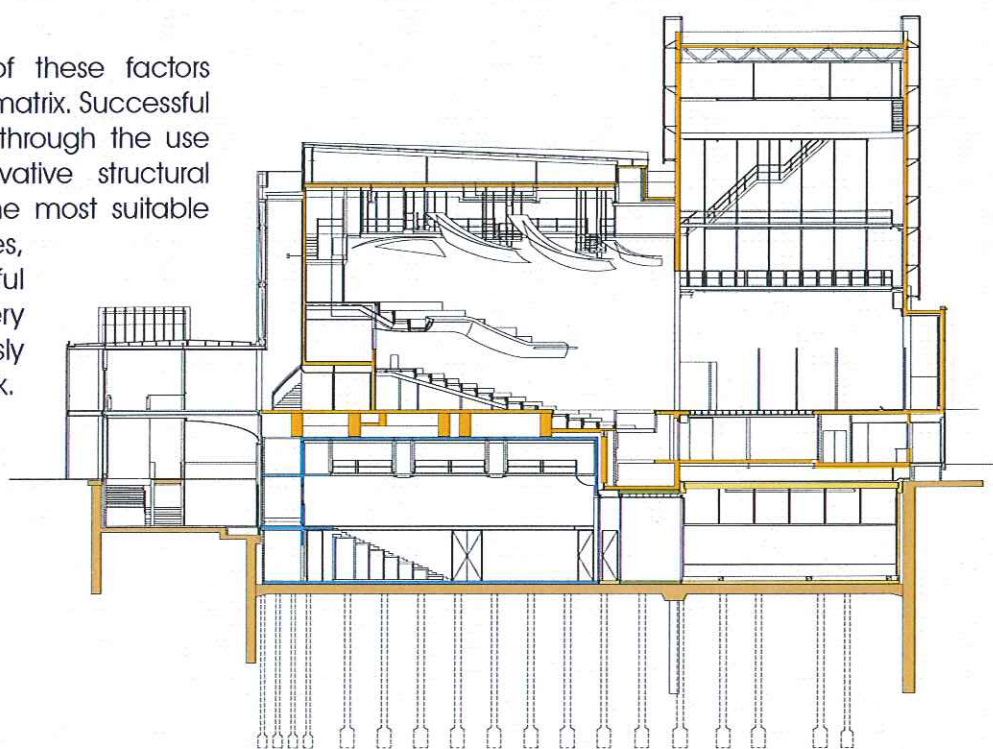


## 8. TECHNICAL COMPLEXITY

The challenging architectural configuration and acoustic isolation requirement was a major aspect of the technical complexity involved. Equally challenging complexities arose from the proximity of the vulnerable heritage buildings to the deep excavation, the high groundwater level, poor site accessibility and limited site footprint.



The cumulative effect of these factors offered a highly complex matrix. Successful resolution was achieved through the use of unconventional, innovative structural solutions that provided the most suitable construction techniques, and facilitated the successful and timely project delivery while simultaneously minimising construction risk.





## 9. COOPERATION WITH OTHER DISCIPLINES AND PROFESSIONALS

Achieving the optimum acoustic isolation was a dominant requirement for project success. Delivering this objective required particularly close liaison with the architect, the acoustic consultant and, equally important, the construction team.



The structural design of the underground external shell required comprehensive analysis with due consideration for soil-structure interaction. Airey Taylor engaged the services of Golder Associates to assist in performing the geotechnical analysis, interfacing with the structural analyses performed by Airey Taylor. This collaboration resulted in optimal structural design of the D-walls and Basement rafts, and unblemished performance.

Developing the design of the P/T belled-end pile required collaboration with the specialist piling Contractor BELPILE Pty Ltd to assess the risks involved in installation and detailing an implementable pile system.

For the design of the Façade elements, Meinhardt Façade Technology were nominated by and engaged through Airey Taylor. The development of the façade solution was performed in close consultation with the structural design.

Interaction with the leaders in the concrete additive industry was pivotal in developing the special concrete mixes specified for the project.

Airey Taylor worked with the architect and the mechanical engineer to facilitate optimisation of the air temperature control through utilisation of some of the structural elements. In all, the achievement made in this important venue was not possible without the high level of collaboration between all of those involved.





## 10. ATTENTION TO VALUE ADDING

A major design objective set by Airey Taylor Consulting was to minimise scaffolding requirements. In addition to conventional methods of using permanent formwork and precast planks, the structural designer employed other design initiatives that were effective in reducing scaffolding; a prime example being that on the Fly Tower roof structure.



Steel trusses were used to form the winch-room end walls. These trusses were designed to be capable of receiving the winch room concrete slab and, following their connection to the roof trusses above them, the reaction forces of the lower level Fly Galleries and the winch room equipment. The fly-gallery loads were able to be transferred through edge hangers that link between the fly galleries and the winch room truss. The roof trusses, on the other hand, were designed to be capable of receiving the winch floor grid, mechanical equipment and the construction weight of the roof deck slab without propping. This facilitated the construction of the fly tower without the need for scaffolding, following a specific construction sequence, ensuring a column-free stage.

Other value adding items discussed in the submission earlier are:

- Utilisation of the structural steel as part of the architectural statement;
- Utilisation of the concrete shell to form the water and vapour barrier at the retaining walls and basement floors and fully discarding waterproofing membranes;
- Use of pore blocking additives to enhance the durability and reduce maintenance of the concrete elements used in the architectural precast cladding panels and the underground external shell;
- Development of P/T belled end Piles (Maintenance free Ground Anchors);
- Optimisation of design through the use of comprehensive 3D Finite Element Modelling.





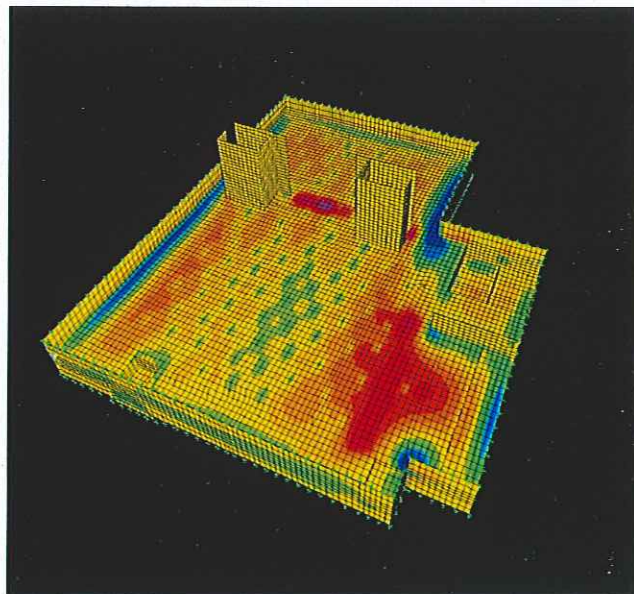
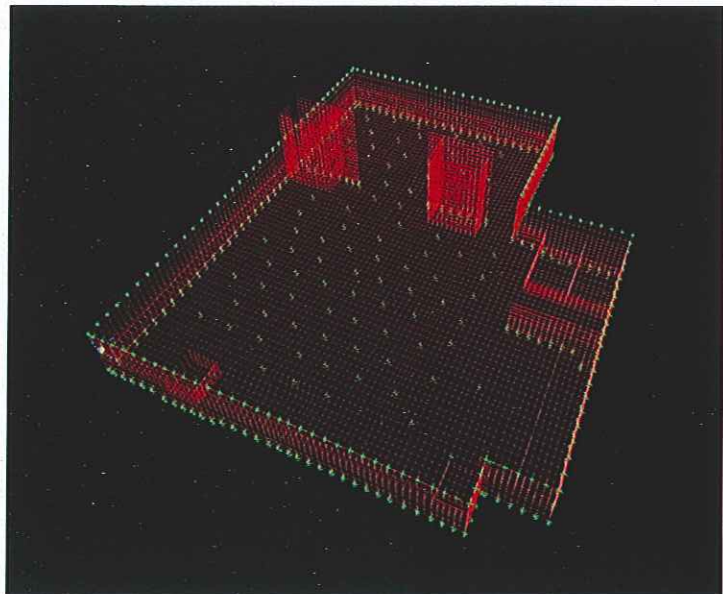
## 11. INTEGRATION AND INNOVATIVE USE OF COMPUTER MODELLING



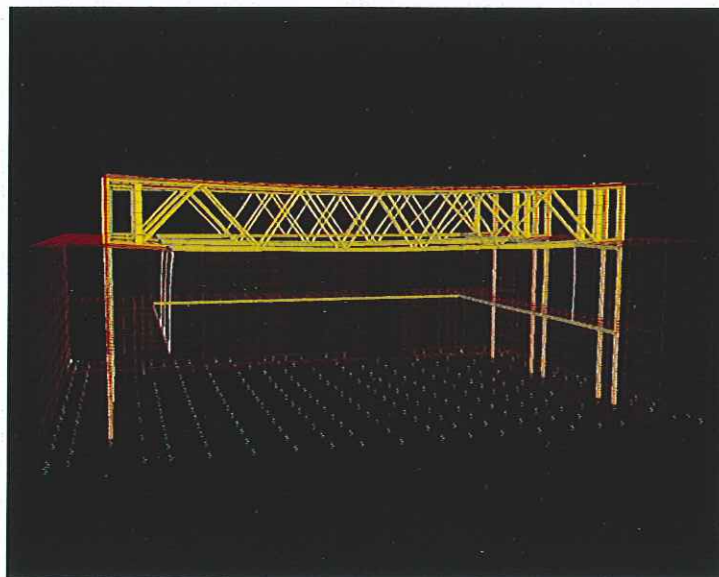
Extensive 3D structural modelling was performed throughout the design stage. For the structural analysis, Airey Taylor Consulting used sophisticated Finite Element Analysis programs for establishing comprehensive structural models and optimising the structural design.

Among the 3D analysis models developed for the analysis of the project are:

- a) Top-Down construction: The structural analysis model of the soil-structure iterative interaction analysis to establish the load sharing of the complex configuration.
- b) Non-Linear construction stage analysis of retaining walls: Modelling considered the different construction stages including the installation of temporary anchors, dewatering, engagement to raft slab and the final construction stage. The comprehensive analysis facilitated the optimisation of the design and detailing of the RC retaining walls.
- c) Basement 2 raft- P/T belled-end Pile analysis model: The model considered multiple arrangements of pile spacing, pile/soil stiffness and patterns. The optimised raft-thickness/pile-arrangement selection criteria included uniformity of service stresses in the raft while keeping high load/capacity ratios for piles.



- d) Studio Theatre model: The model included the main trusses, walls, floating slab, gallery-floor and roof lid to assess the stress distribution in the walls and the bearing pads and locate the optimum type, size and location of the bearing pads.

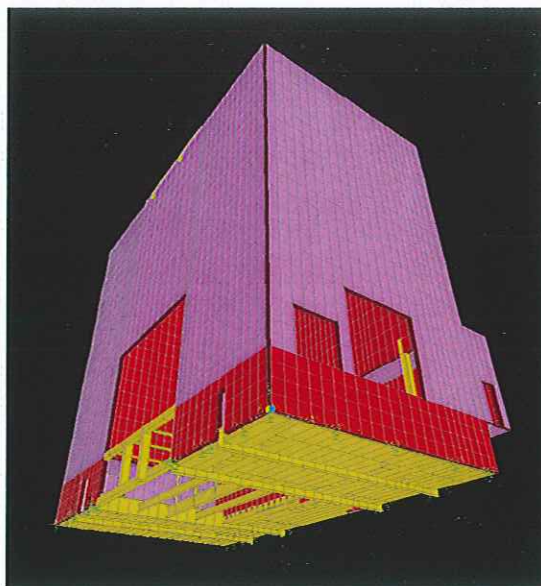






e) e) Main stage and Fly Tower model: Comprehensive analysis of the member forces under the staged construction of the composite transfer floor was performed as well as analysis of the Fly Tower winch-room and roof trusses with due consideration to the construction stages discussed in (10).

f) f) Level 3 Eastern Mechanical Plant cellular box transfer structure: The grouted reinforced blockwork walls under the mechanical plant were engaged with top and bottom concrete slabs to form a rigid transfer structure. This provided the design capacity in the complex configuration of the area.



g) Main Auditorium Roof model: Grid analysis of the roof's composite steel beams was performed for the staged construction of the complex configuration.

h) Integrated Bronze/White box model: Comprehensive analysis performed for this section of the building had a pivotal role in achieving the light structural configuration in the striking foyer architecture.

