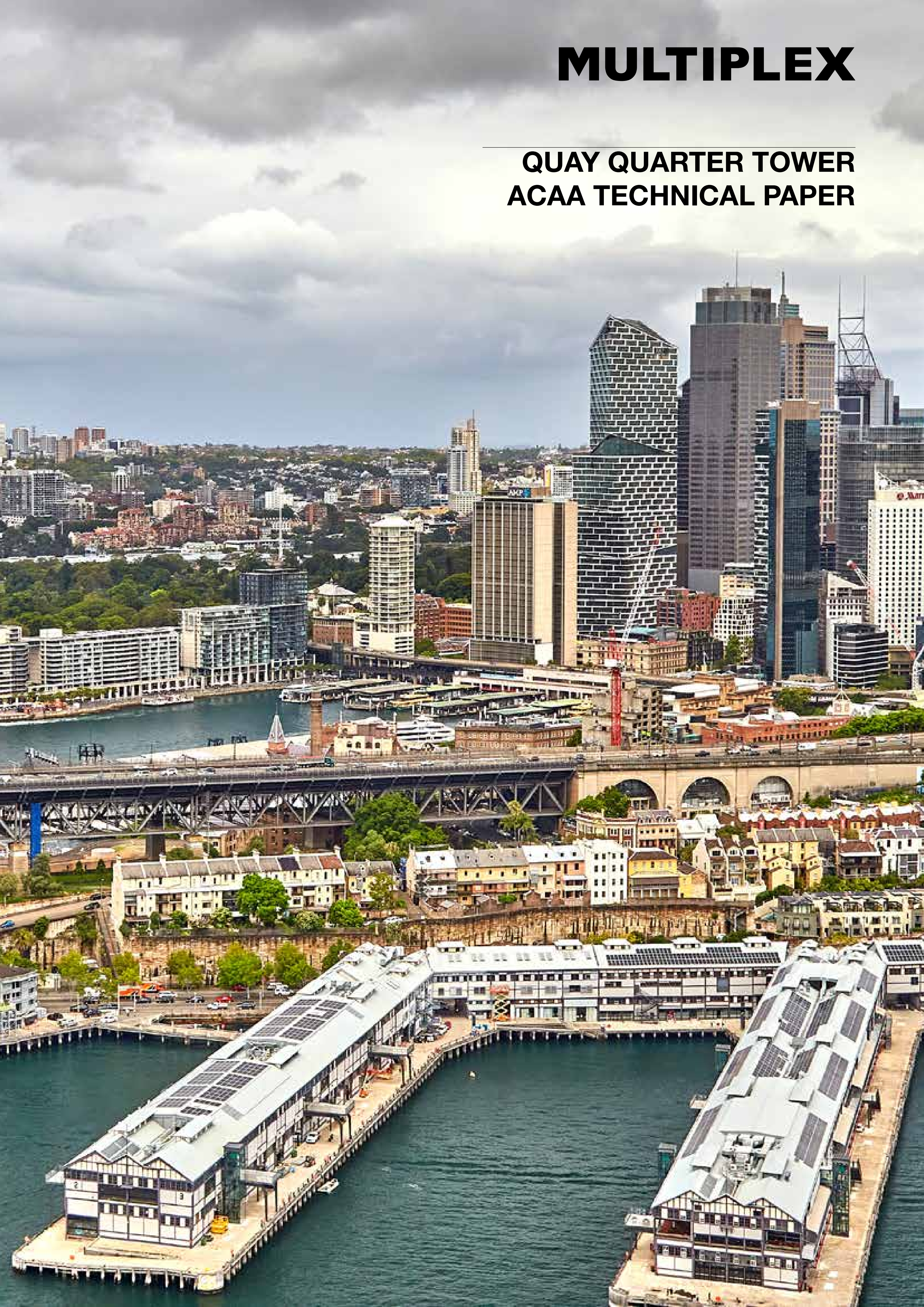
MULTIPLEX

QUAY QUARTER TOWER
ACAA TECHNICAL PAPER



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1. Project Description

1.1 Project Overview

Quay Quarter Tower (QQT) is a 50 Storey commercial building at Circular Quay Sydney, the centrepiece of AMP Capital's Quay Quarter Precinct development that is revitalising the area with new commercial, retail and residential spaces. The QQT project involved the reuse and adaptation of the existing 46 level AMP Centre at the heart of the precinct, via the demolition of 1/3 of the total floorplate of the existing building, followed by extending the building both vertically and horizontally with 40,000m^2 of new floor plate and a new core consisting of 5 lift banks. This new structure and its highly complex and ultimately successful tying back into the existing building, constituted a world first in reuse and adaptation, enabling 66% of the existing building to remain.

This significant reuse allowed for a carbon saving of 8,000 tonnes and achieved a 6 Star Green Star rating, which demonstrates world leadership for sustainability in the built environment. The end product is a structure featuring 49 floors of premium office space, 4 levels of retail space, 3 levels of car park and the attainment of a 5 star NABERS rating.

At the time of demolition, QQT was the tallest demolition project in the world and the largest scaffolding assignment in the southern hemisphere. A unique build, this exciting and challenging project presented a number of design, program, safety, and construction difficulties that needed to be carefully planned and managed by Multiplex in close collaboration with Owner and Developer, AMP Capital, Architects 3XN & BVN and Engineers BG&E and Arup over the 4 year construction period.

Extensive workshops that featured collaborative knowledge gathering and dissemination took place that allowed innovative construction solutions and techniques to be developed – in an open-minded planning, design, engineering and construction team environment. Achieving best project outcomes was front of mind for the entire team throughout.

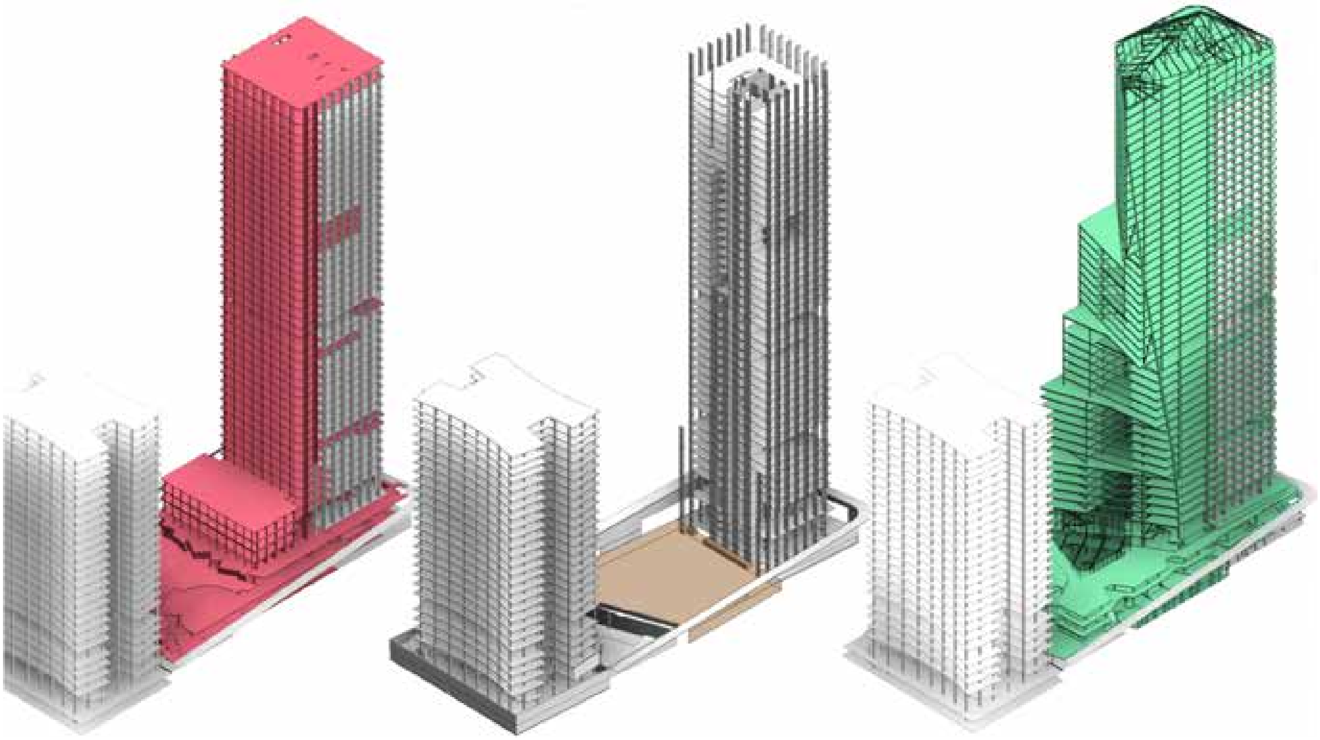


Figure 1 Existing building in red showing extent of demolition (left), the partially demolished building (centre), and the final product following the construction (right).

1.2 Project Scope and Contract Details

In 2018, Multiplex was awarded the Design and Construct Contract to deliver the QQT Project for AMP Capital, from preliminary design, through to construction.

Multiplex has a proven track record for the successful delivery of complex and challenging construction projects, on time and to agreed costs, whilst always ensuring that the highest quality and workplace, health, safety and environmental standards are maintained.

The building involved extensive strengthening requiring 750t of temporary steel, part demolition of 46 floors of existing build concurrently with the construction of a new core and composite structure requiring 7000t of new steel. The project commenced on 23rd February 2018, with the following key objectives:

- A new tower building designed by Danish Architect 3XN, involving 5 rotating blocks that take advantage of the project's location over Sydney Harbour and its northern outlook
- Conversion of an 'A Grade' tower to iconic 'Premium Grade' building
- Increase of GFA to 102,000m^2
- Maintenance of the heritage-listed and interfacing Bennelong Drain (beneath site) together with maintenance of 33 Alfred tower (north of the site)
- Excavation of new basement level
- 6 Star Green Star Office v3 Design (targeting As-Built)
- 5.5 Star NABERS Office Energy (target)
- WELL Gold
- 6 stages of handover to allow for early tenant access

Figure 2 The existing building (left), and the completed product (right)

2. Key Design Insights

2.1 Design Overview

2.1.1 Structural

Designed by Rankine & Hill for a 50 year design life, the existing building was constructed between 1973 and 1976, and was due to come to the end of its design life in 2023. The structure consists of precast columns extending the full height of the tower, with conventionally formed RC floor beams between the cores and columns, complete with precast slab infills between the floor beams.

The design of the new QQT project involved the demolition of all elements north of the existing core from L00-L45 to allow a new larger extension to be constructed. The remainder of the building was to be retained, and necessitated structural strengthening to elements of the existing building to be carried out concurrently, thereby allowing for its upscale to meet current Codes and Standards and provide for an additional 50 year design life.

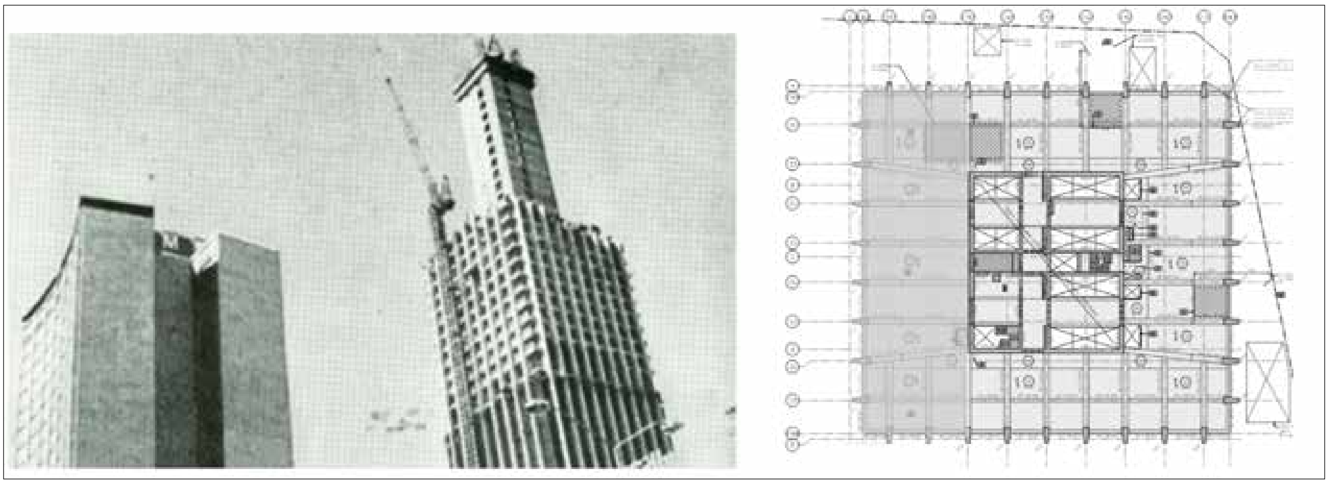


Figure 3 The existing building under construction, and floor plate of the existing building.

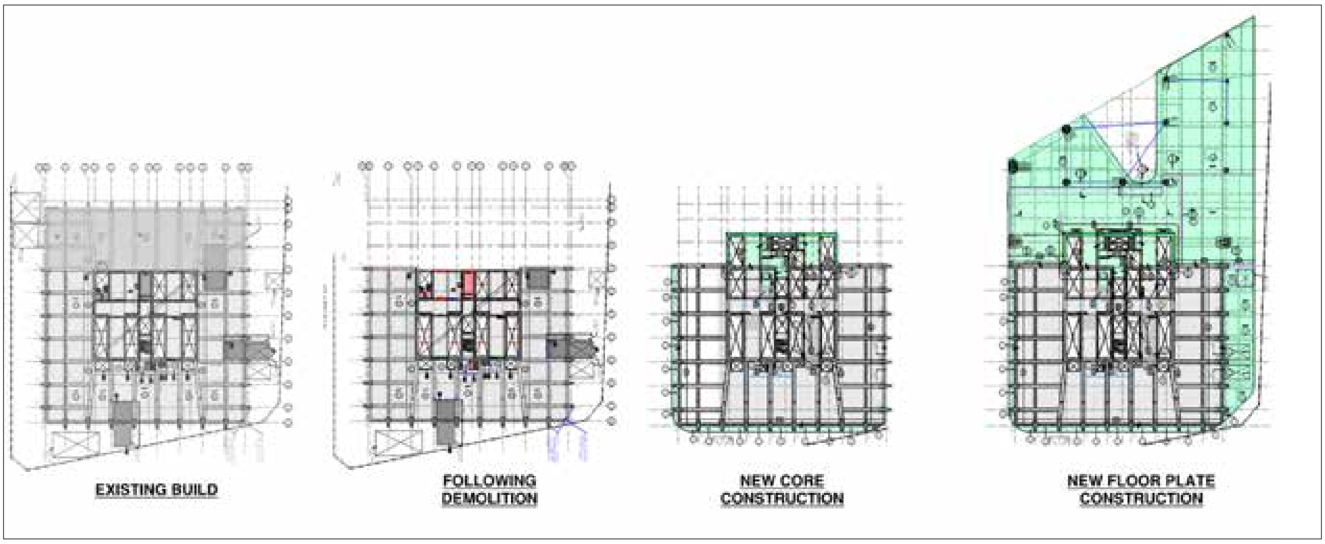
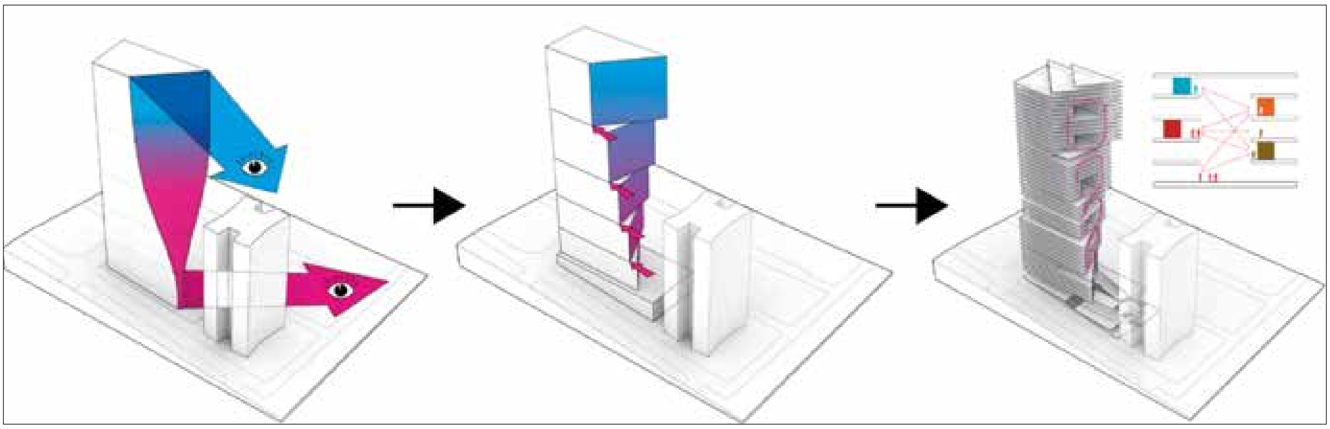


Figure 4 Plan View of Existing build (furthest left), building following demolition (centre left), building following new core (centre right), and new floor plate extension (furthest right).

Figure 5 Concept Shape of the building, developed into the final QQT Design



2.1.2 Architectural

Designed by Danish Architect 3XN, Quay Quarter Tower advances the latest thinking in workplace architecture to enable high performance business. The tower's rotating forms and unique façade maximise natural light and harbour and district views, while ensuring excellent thermal comfort. Spiral staircases and multi-floor atria promote human interactions and better business functionality.

The 5 vertical villages form the various 'blocks' of the building to provide the following:

» Uninterrupted views at all levels

» Atria which encourage interconnectivity of workers

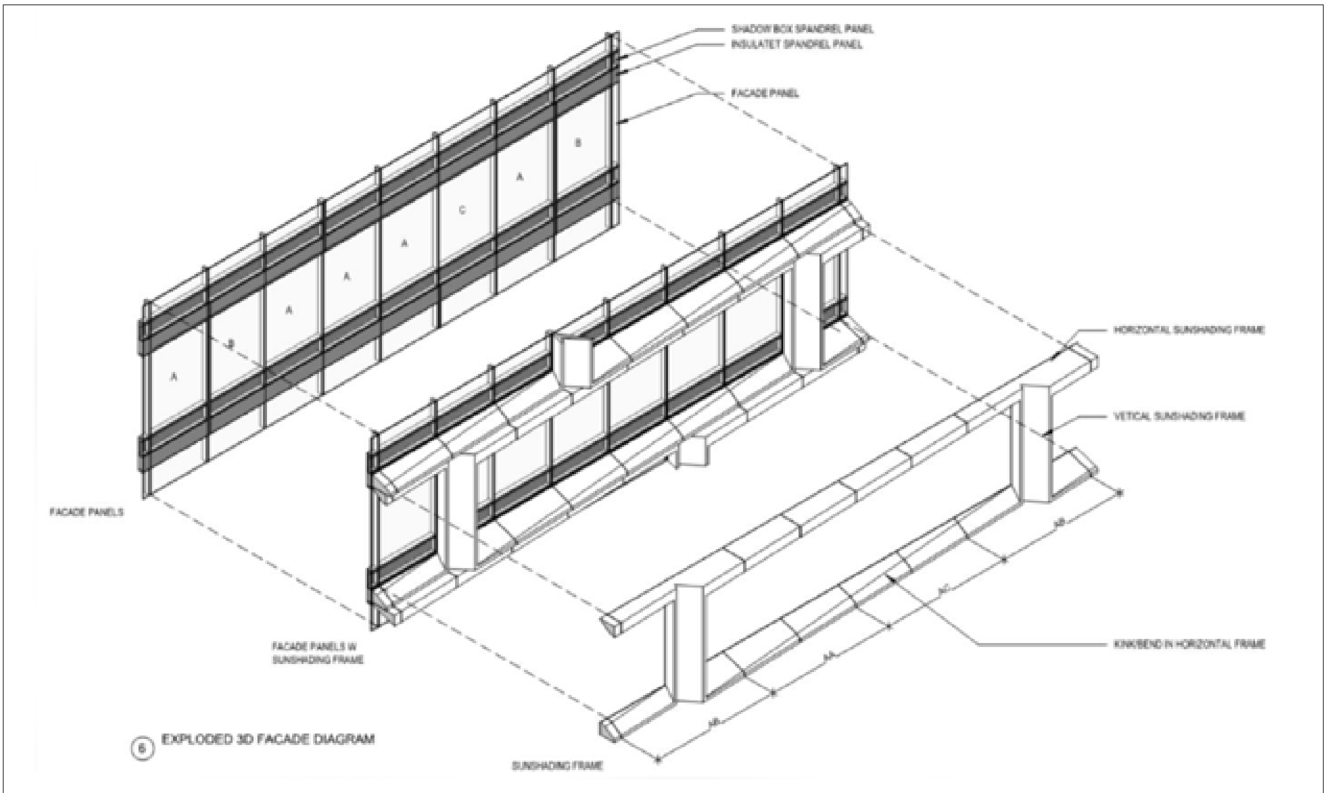
» Unique form and function of the buidling.

The external envelope of the building is a façade system which acts as an architectural feature while affording thermal function. External aluminium sunshades provide occupants with protection from sun and glare, and protrude differently across all elevations:

» West and east elevation sunshades extend 900mm outwards from the building, hanging down 300mm to ensure shading during morning & afternoon sun

» North elevation sunshades are flat allowing maximum winter sun while not impacting on the expansive harbour views.

Figure 6 Exploded view of the façade system comprised of curtain wall and external aluminium sunshades



2.2 Structural Design Risk Management and Testing

The structure of the QQT building is a hybrid system combining existing and new structure. In order to incorporate risk management into the design phase of the new structure, a highly detailed simulation via structural analysis modelling took place that incorporated the existing building characteristics, the behaviours of the new build, the differential movements between the two elements, along with the time dependent interactions such as shrinkage and creep - and the associated structural impact.

The in-situ properties of the existing concrete elements, including core walls and columns, were determined through comprehensive non-destructive and destructive testing programs that included over 3000 concrete core samples. The detailed model, which included the in-situ material properties, allowed the design team to understand the behaviour of the structure during the demolition and rebuilding, and to adapt the design to reduce construction risk. To verify the building movements and the accuracy of the structural analysis, several monitoring instruments including accelerometers, tilt sensors, strain gauges and positional survey points were installed at different locations in the tower throughout the project providing live tracking and information on the building behaviour. The structural analysis was calibrated progressively during demolition to represent current site conditions.

The time dependant properties of the new concrete elements, including shrinkage and creep, were determined in accordance with relevant standards and incorporated into the analysis. The model, which included the above detailed in-situ material properties, provided an exceptional opportunity to the design team to understand the behaviour of the structure during the demolition and construction, thereby reducing the risk of potential damage during construction while upcycling the build for an additional 50 design years.

Refer below flow chart of the iterative process throughout the testing procedure.

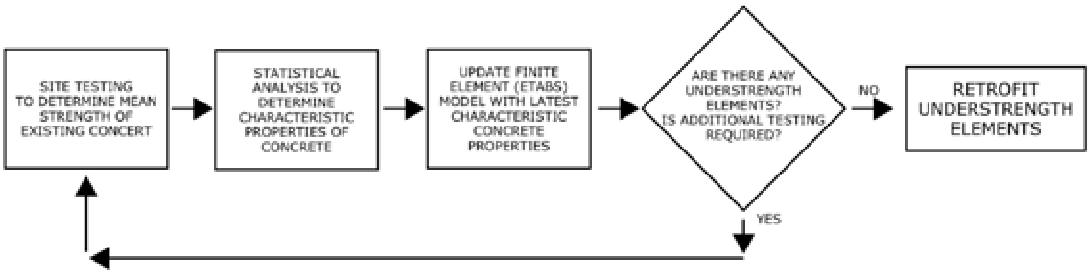
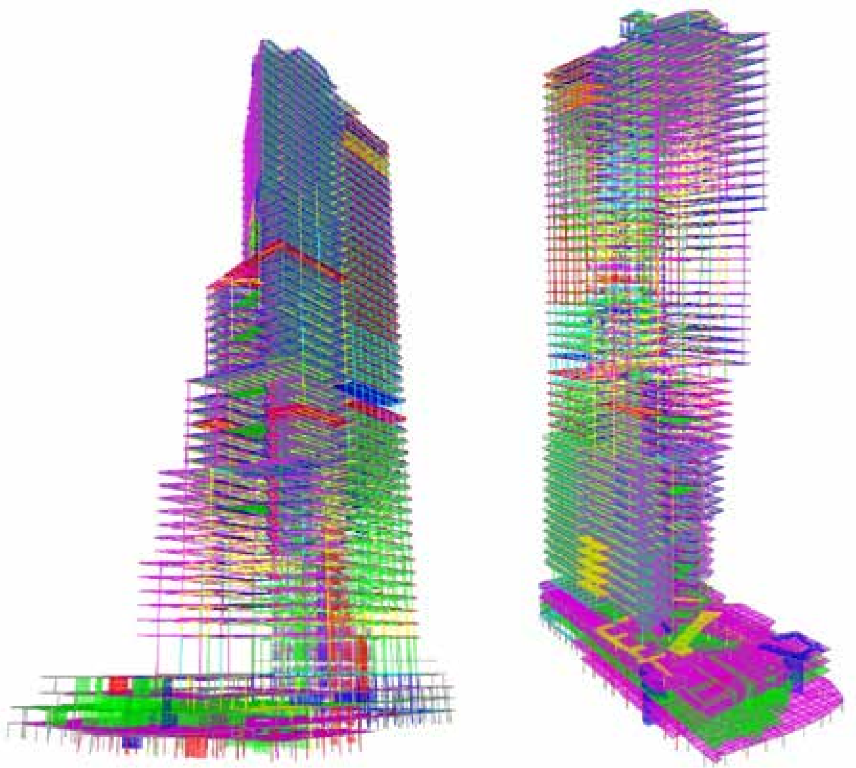


Figure 7 Finite Element Analysis Mode of the project, containing all structural elements



2.3 Maintaining Whole of Life and Adaptation of New Construction Codes

A key element of the project was maintaining 66% of the existing structure and extending the design life by an additional 50 years. To achieve this, all existing elements were examined (as detailed previously) and adapted to meet new construction codes. Namely 3 key differences were identified from the 1970 code requirements:

1. The lap splice length for reinforcing steel has increased by approximately 50% from previous design codes to the current code. To accommodate the reduced splice length, the capacity of the walls and columns in the tensile direction had to be reduced to meet the specific difference in capacity.
2. Confinement reinforcement details (the closing, hooks and returns of reinforcement steel) has dramatically increased requirements under the new AS 3600 code. To meet the new code, a performance solution from international codes coupled with examination of the capacity of specific columns under load took place, to identify and strengthen where required.
3. The earthquake code (AS1170.4) has changed during the last 40 years, with the required earthquake loads applied to buildings significantly increased. The existing building details underwent a full assessment and where elements of the build had insufficient lateral, torsional & flexural load capacity, the additional strengthening required was undertaken.

2.4 Strengthening of Existing Building

From the above, detailed assessment of the existing building involving destructive testing, non-destructive testing, assessment of existing details, and upcycling the existing building to meet required codes & standards, multiple different strengthening details were utilised for the individual situations throughout the tower:

2.4.1 Steel Jacketing

8 core walls were strengthened with steel jacketing to increase the compressive strength of the walls by an additional 50% compressive capacity.

2.4.2 Complete Demolition & Rebuild

An existing core wall was completely demolished and rebuilt as the destructive core sampling determined that local portions of the core included concrete with insufficient strength that meant it could not be retained or strengthened.

2.4.3 Carbon Fibre Installation

28 walls throughout the tower were strengthened for tension with carbon fibre laminates at the south side of the building. This was due to the wind load applied on the south of the building that in addition to the cantilever on the north side of the building, resulted in a ‘pulling’ or tensile force on the south side of the core.

2.4.4 Combination Steel Plate & Carbon Fibre

125 coupling beams (beams which tie individual lift cores together) were overloaded under the combined effects of axial, shear and flexural loads. The extent of failure by the existing beams ranged from 20% to 50%. These beams were strengthened using an optimised combination of steel plates to accommodate compression, together with carbon fibre for tensile loads.

2.5 Key Structural Design Characteristics

There are multiple key structural design characteristics of the QQT project including:

- Connection of the new core to existing
- Extensive cantilever construction tied to an existing building
- Implementation of a Tuned Mass Damper
- Differential shortening and movement across floor plates.

2.5.1 New Core

The new core is a 3 sided concrete construction stitched to the existing building. To do so, over 2000 chemically fixed steel anchors (each 2.4m in depth and 50mm in diameter) were drilled in to the existing concrete core and lapped into steel reinforcement of the new core.

To accommodate the difference in settlement between the new and existing cores (and avoid applying shear load to the 50mm diameter reinforced bars), a 400mm pour strip was introduced and infilled 56 days following the new core construction. In addition, development & implementation of low shrinkage concrete further controlled the reduction of settlement of the new core during the construction process.

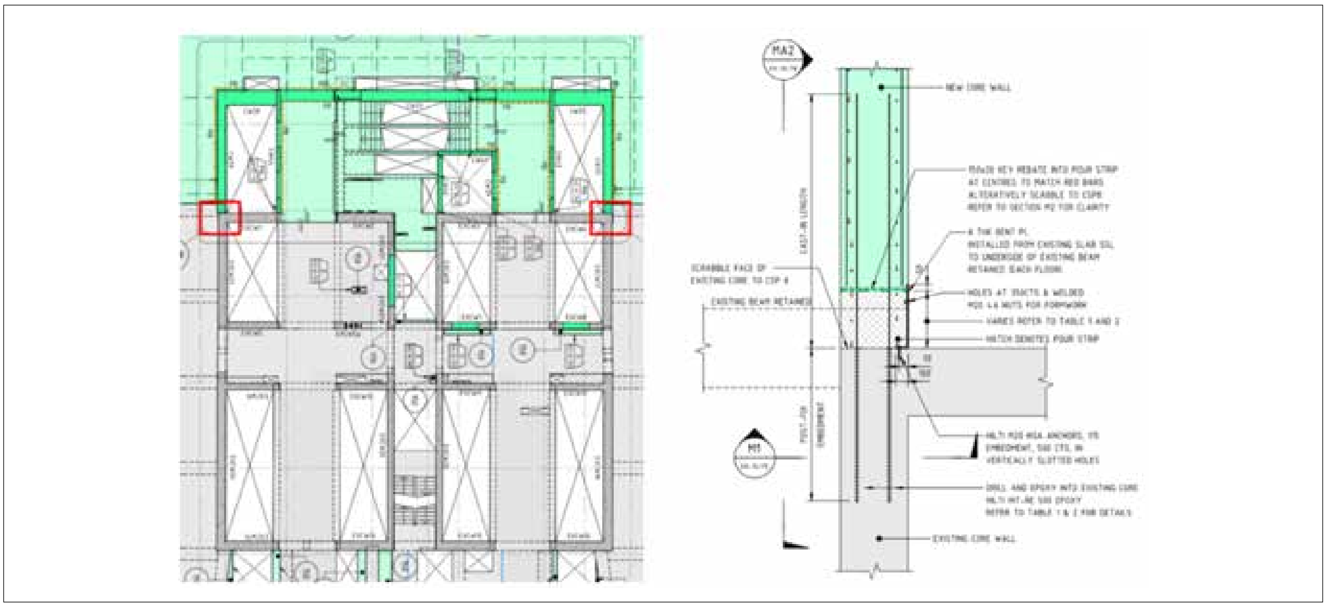


Figure 8 Plan view of existing & new core (left), with the detailed stitch connection (right). The grey is existing and the green is the new construction.

2.5.2 Cantilever Design

The cantilevers of the project are the most structurally challenging elements, with L34 projecting over 25m past the lower floors.

These cantilevered elements are supported via columns that are hung from structure above, connecting into an incline column that runs the full length of the building. This key design feature of hanging columns reduces the required depth of the horizontal beams & floor depth of the cantilever structure.

With the vertical load of the hanging column acting on the incline column, a lateral load is then imposed on the slab, and is required to be taken back to the core.

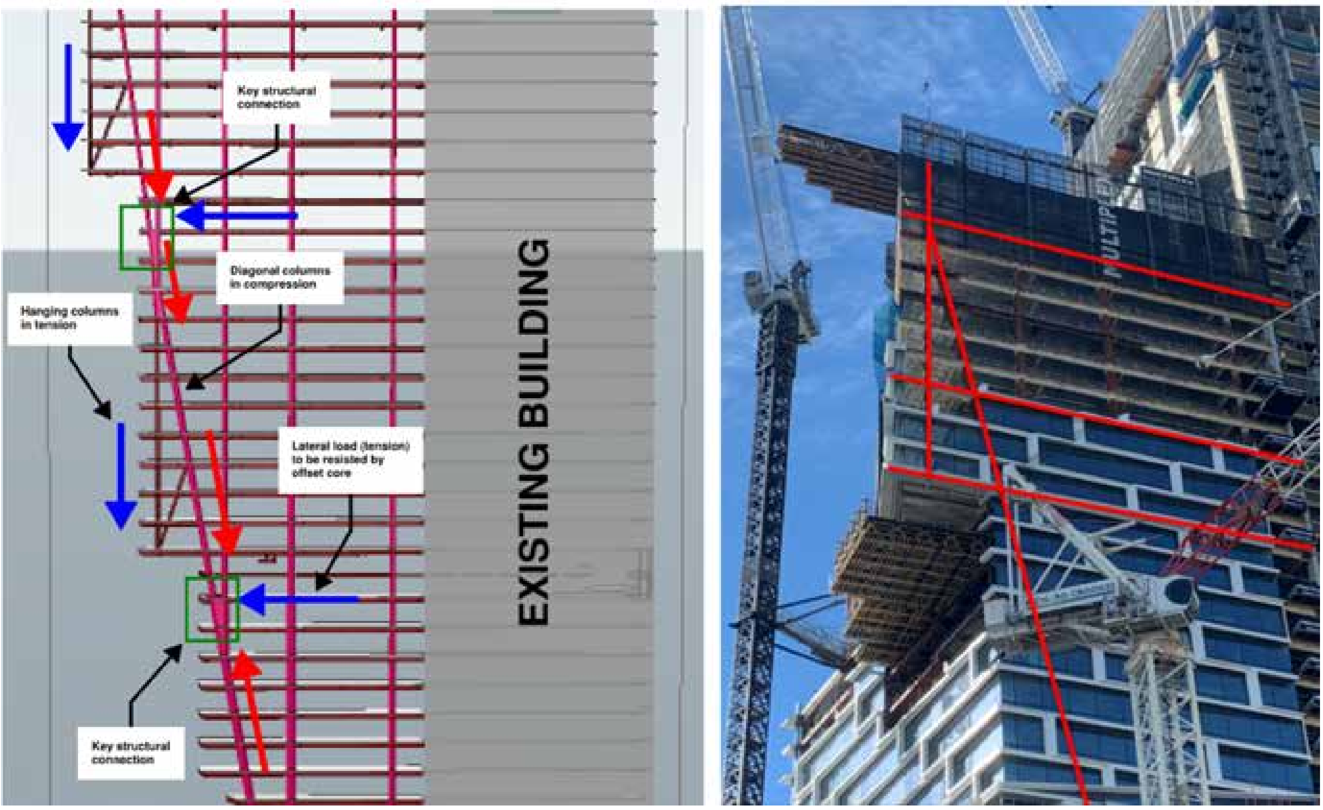


Figure 9 Section of building and load path of Cantilever design shown (left), and photo of hanging and incline column marked up on the project under construction (right)”

There is no direct load path from the incline column on the west elevation to the core, as the incline column is offset in plan view from the core. As such, the offset tensile load path is required to travel through an upgraded slab & steel beam design as per Figure 10.

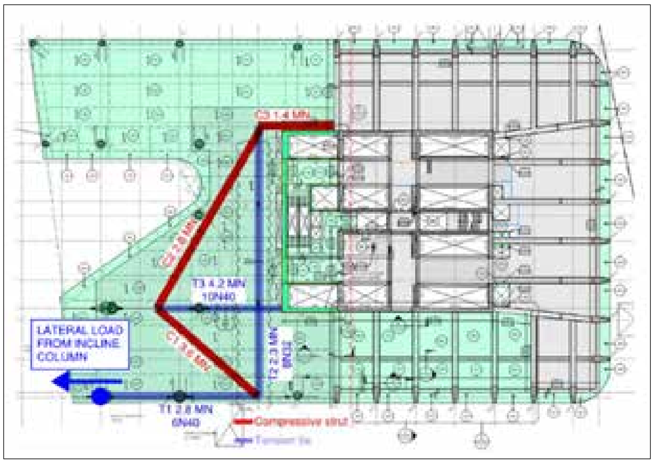


Figure 10 Off set load path from incline column to core

2.5.3 Tuned Mass Damper

The calculated acceleration of the building at the north-west corner of the top floors under service wind loads was higher than the limits specified in international standards and guidelines. The damping ratio used in the calculation was verified by a mass excitation site test. In order to reduce the service acceleration of the building, a TMD (tuned mass damper) was designed and installed on L46.

2.5.4 Differential Settlement

Building shortening and settlement occurs through natural compression and shrinkage of materials, and is particularly significant at QQT where new structure connects to existing. This results in unique and varied shortening across a single floorplate.

At QQT, the varied shortening across a single floor plate is consequential from the following:

» Column concrete shrinkage: As concrete cures, shrinkage occurs which reduces the overall height of the column in question. This drives the RL of the slab above to be slightly reduced, which takes place on the north side only and not the southern

» Existing Core Shrinkage: The new core is tied back to the existing concrete core. As the large mass of the new concrete core shrinks during construction, this pulls the existing core (and adjacent columns) downward.

» Building compression: As additional floors are built on top of floors below, the floors experience a compression load. This load increases as the structure grows.

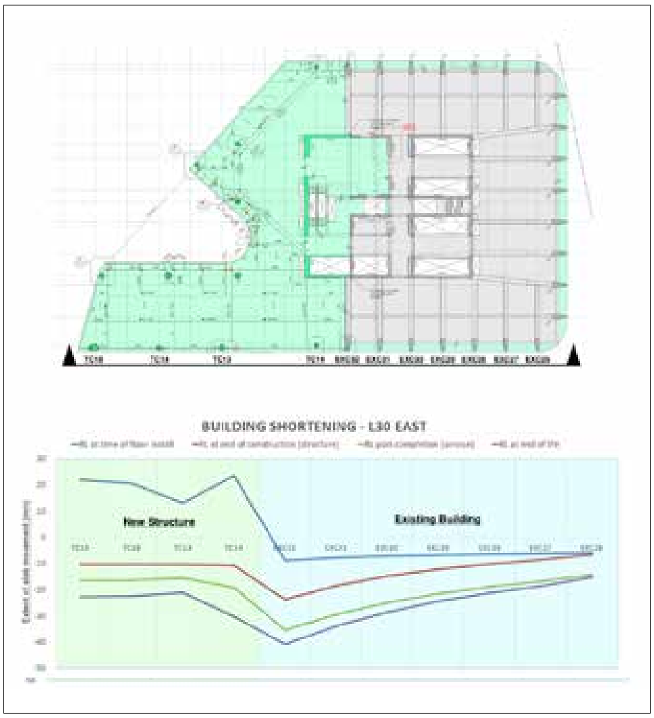


Figure 11 Differential settlement across the building elevation

The Figure 11 plan view and elevation, illustrates the anticipated deflection of the structure from the northern most part of the building to the southern element, at various stages of the building from floor install to end of service life. As visible in the graph, the new structure to the north shrinks significantly compared to the existing, where the concrete has already completed curing.

Further, the shortening takes place at different rates on each of the elevations (east and west) due to the structure having uneven loads resulting from the cantilevers and load paths of the building.

3. Construction Methodology

3.1 Jump Start Construction Sequencing

With time being an increasingly critical component in construction projects, Multiplex worked with AMP Capital to develop a ‘Jump Start Construction Sequence’. This added value to the project by allowing the partial demolition (top down) of the existing tower to be completed concurrently with the construction of the new composite structure and core extension (bottom up). This complex construction approach resulted in a 16-month program advantage for the project, as conventional construction relies on the demolition being complete before commencement of construction occurs.

To achieve the ‘Jump Start Construction Sequence’, complex structural sequencing challenges were resolved with our structural consultants, for temporary staging of the new structure. This allowed the northern tower extension to be treated as an independent structure until the adjacent existing tower was partially demolished and structural connection back to the existing structure could be achieved.

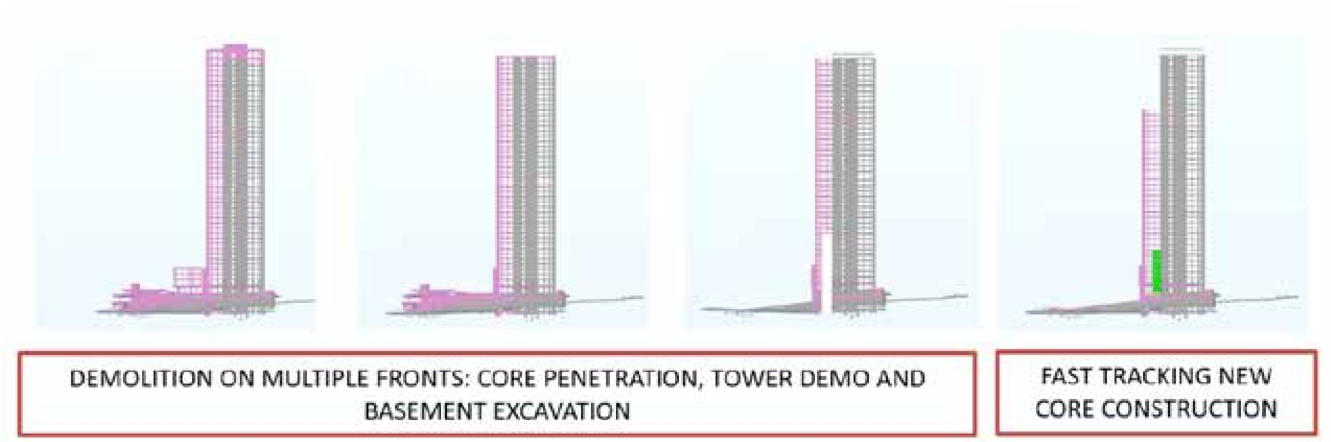


Figure 12 Demolition of tower underway (left), penetration through existing building (centre), fast tracked core construction through existing building whilst demolition above (right).

The 'Jumpstart Construction Sequence' involved the following:

» Full in-ground excavation and construction of new footings at B5 beneath the ongoing structural demolition taking place above.

» Penetration through the existing building from L00 – L11 to allow the fast tracking of new core construction through the existing building to take place whilst demolition was taking place above concurrently.

» Full construction of North Structure up to L11 whilst demolition was ongoing, before bridging over the demolition component back to the existing building as the demolition continued.

Figure 13 North Jumpstart structure bridged across to existing building and demolition complete (left), New tower construction underway (centre), completed building (right)."

3.2 Site Logistics, Constraints & Interface

Due to the large volume of traffic movement in and around site together with it constricted space, on-site logistics required careful consideration and planning.

In total, 5 tower cranes were employed on QQT, managed by a dedicated logistics team who coordinated day-to-day works and major deliveries. A key challenge was transporting the large numbers of personnel on site via internal and external hoists as the work population would peak at upwards of 1200 workers per day. This required the use of 9 external hoists and 12 internal lifts for personnel transportation.

With a limited laydown area available due to council restrictions, and ongoing interface with adjacent construction sites, all deliveries had to be booked and managed through a specialised Multiplex Site Logistics team, members of which delivery schedule meetings on a daily basis.

The prominent position of the project required interface with public transport networks, major public events and other major developments in the Circular Quay precinct. The project team proactively collaborated with local authorities and other development teams to minimise the impact of construction activities on the precinct and nearby stakeholders.

A dedicated liaison team was set up to ensure successful logistics management and effective day to day operations for each company, through well-planned communications and regular inter-company consultation. Close stakeholder consultation has helped the project team understand stakeholder concerns and to manage expectations during the various phases of construction. In collaboration with the main contractor on the development's residential project, weekly notifications were issued to neighbouring stakeholders for any expected impacts due to construction works, and monthly construction updates were provided that focused on the positive outcomes of the development.

3.3 North Cantilever Elements

To accommodate the unique design of QQT with its cantilevers and shifting geometry, prefabricated temporary truss modules were craned into position to provide both edge protection and working decks for the floors above each of the large cantilevered elements of the building. The modules weighed up to 10 tonnes and input from different trades during the coordination phase was a key factor in their design and fabrication. Prefabrication of the modules off site increased installation efficiencies on site, thereby boosting productivity and maximising crane utilisation for other lifts. The prefabricated modules, which later formed a large working deck, encapsulated the North West cantilever to allow structure trades, façade trades as well as fit out trades to safely complete their works.

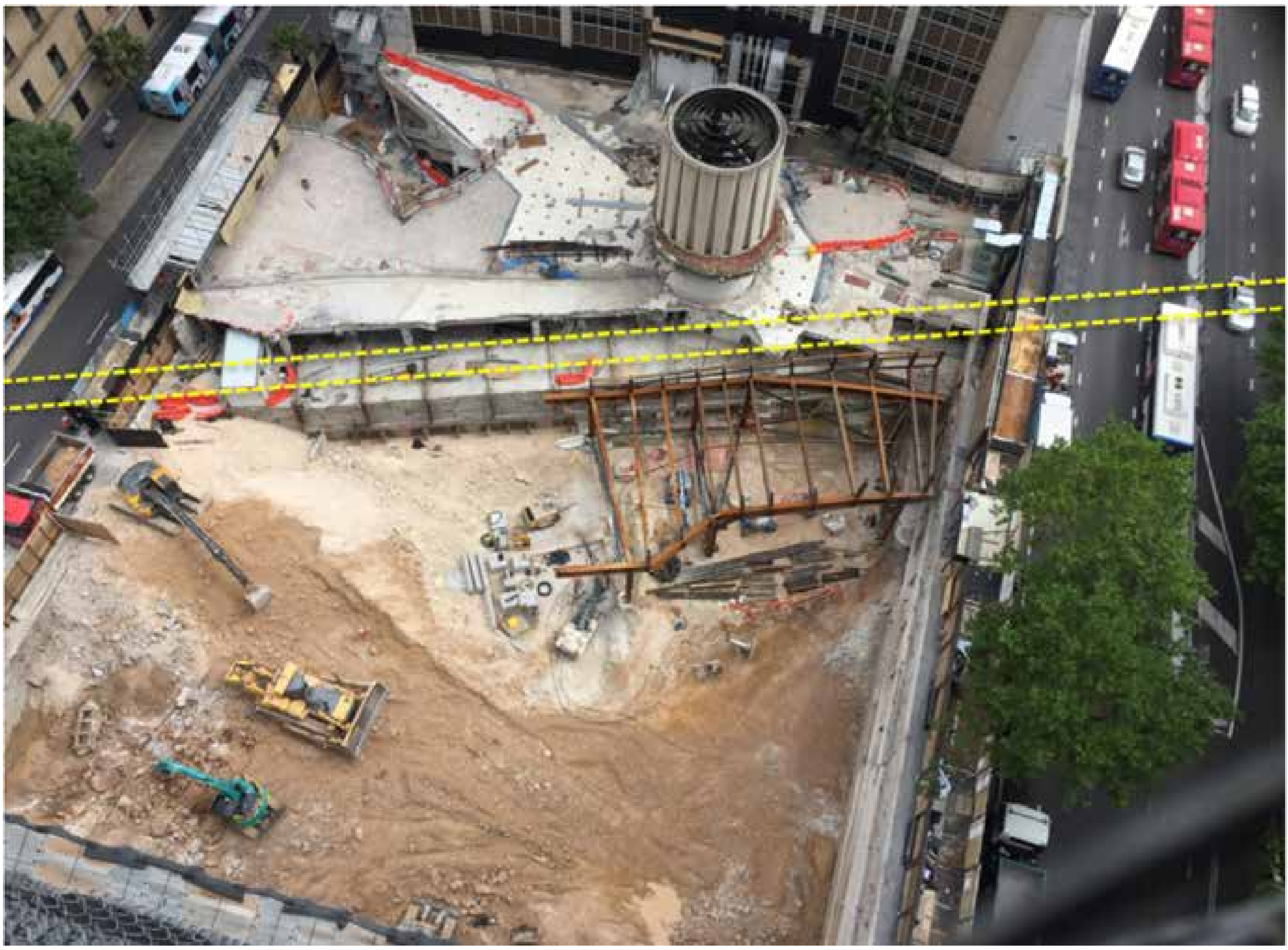
Figure 14 L33 Cantilever Deck Construction

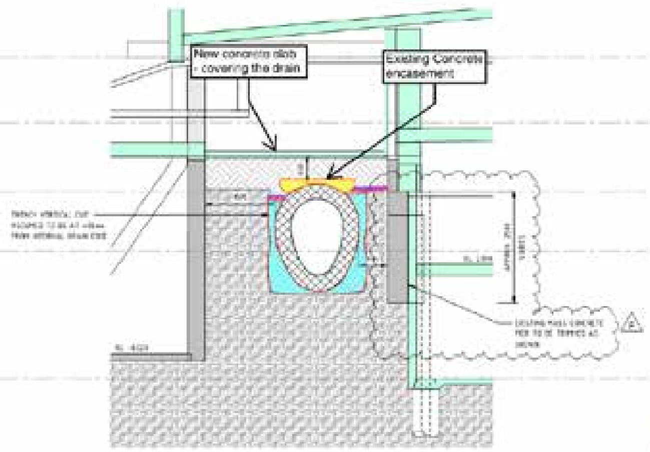
3.4 Management of Heritage Elements & Bennelong Drain

At in ground level, the challenge involved retaining the Bennelong Drain heritage stormwater channel that runs across the site while demolishing the surrounding existing structure, excavating an additional basement level directly adjacent to it, and building directly over the live service.

Through FEA analysis of the masonry drain and impact of the excavation, the extent of required surrounding earth to remain intact, could be determined along with required excavation sequencing to adequately protect the heritage item.

Careful planning of this area meant that we were able to successfully monitor and retain the heritage structure during construction. Refer below for details of the excavation and surrounding construction





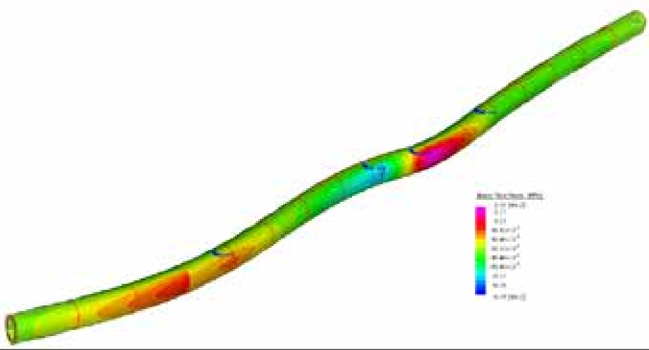


Figure 15 Site photo showing location of Heritage Drain, along with details for management throughout construction.

3.5 Differential Settlement, Pre-Setting & Building Monitoring

As detailed previously, there was extensive differential settlement between the existing building, new floorplate, new core, and a difference across floorplates in an east-west direction.

To accommodate this, a collaborative process was required where Multiplex developed the construction sequence to meet the requirements of the program and buildability, with key parameters being:

- Demolition program
- Core program ahead of the floorplate construction
- North floorplate construction program
- Façade program that lagged behind north floorplate construction
- Fit out across the floorplate.

Following this, the required pre-setting was workshopped with the design team to determine the specific pre-set of each column on each floor across the building, followed by the pre-set requirements of the façade system.

The below graph shows an example column in the building and the shortening from installation through to end of building life across all floors.

- At time of install at L20, the column is pre-set 40mm above design RL
- Following façade install (7-10 floors behind floorplate) the point has shortened to 15mm above design RL
- It continues to shorten as additional construction takes place
- Timed to a final point of 25mm below design RL at end of building life.

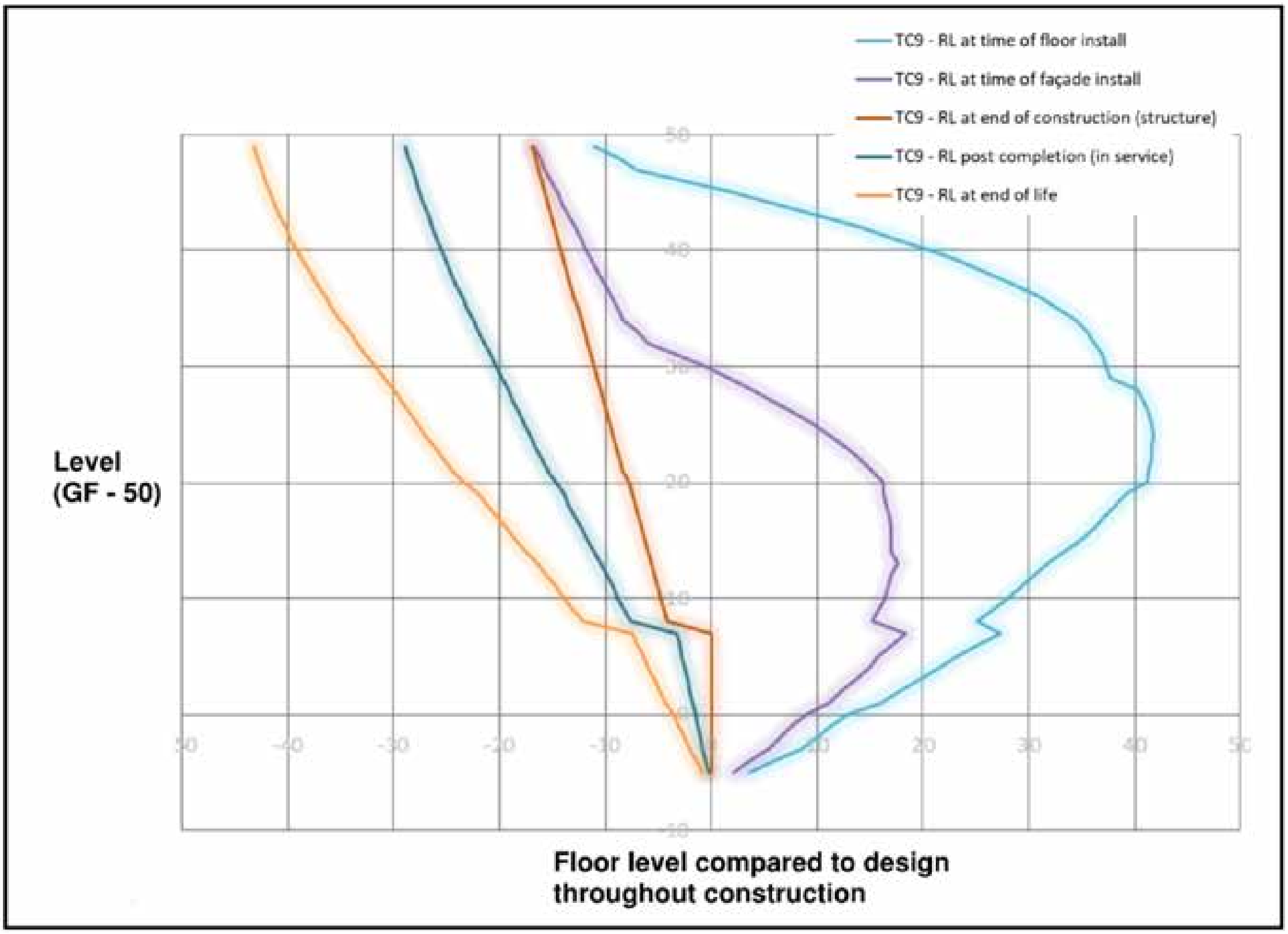


Figure 16 Pre-set values of a column, and the settlement of the column over time from install to end of life.

4. Project Outcomes

4.1 Environmental Impact

Quay Quarter Tower features world-first sustainability initiatives including the retention of two-thirds of the building's original core. This involved constructing the new tower around the existing core, and incorporating carbon-reduction techniques that are cutting edge across the globe. The team achieved a carbon saving of 8,000 tonnes (equivalent to approximately 35,000 flights from Sydney to Melbourne) and a 6 Star Green Star rating, which demonstrates world leadership for sustainability in the built environment.

The facade includes high performance glazing and external sunshades that reduce heat and glare from 24,714kWh to 17,205kWh (a 30% reduction in external heat) thereby improving thermal comfort for occupants and lowering AC energy consumption.

Internal lighting is high efficiency, low energy LED – 33% lower than NCC 2019 maximum for all typical floors; whilst the chillers boast high efficiency refrigerants that are zero ozone depleting, non-flammable and have ultra-low global warming effects.

During the ongoing operation of the building, in addition to reduced energy, the building will contain a plastic free food court with only compostable packaging used with all aspects of the food, packing, services utensils being able to be composted and returned to the soil.

4.2 Fostering Learning & Education

Multiplex is an advocate of training management, skills development and apprenticeships. Our commitment is demonstrated through our in-house and external training and development programs that encompass a broad range of cohorts including young and diverse talent, candidates new to the industry and those suffering high levels of disadvantage. These programs include:

» Cadet and Graduate Program that includes structured training and rotation through all aspects of the business

» Apprentice Program that includes secondment to a range of subcontractors, structured training and a 6 weeks rotation through the Multiplex Centre for Excellence

» Coaching & Feedback, Mentoring and Feedback Tools

» Face-to-Face workshops and programs that enable in-depth, experiential learning

» Virtual Workshops involving leaders and experts from the business

» Online Courses: Built for Multiplex by Multiplex, and available to anyone, anywhere, anytime

» Trainee and Work Experience Program: The design and development of training and employment solutions that assist in supplying a 'job ready' labour pool that meets anticipated skills shortages.

4.3 Women in Construction

Multiplex has been developing its systems, innovative thinking and relationships to offer all people, including those of all genders, nationalities, cultural, sexual orientation, religions and socioeconomic backgrounds, the potential of employment with Multiplex. Our Diversity program is made up of a number of initiatives one of which is the Jump Start program that explains to female high school students what a career in construction has to offer.

The QQT team hosted a Jump Start site tour for Girls from Cerdon College in Years 11 and 12 girls with students given the opportunity to tour the project and understand what the construction industry has to offer as a career.

The site tour included:

» A detailed discussion and explanation of QQT's design

» Specific engineering innovations including the double decker lift system

» The structure's 3D CAD model

» The importance of ergonomics in supporting the environmental wellbeing, productivity and efficiency of occupants following practical completion

» Personal accounts from female Multiplex employees based on site.

The QQT team continued the second stage of the Jump Start program despite COVID-19 restrictions, by hosting a further virtual workshop for additional students from Cerdon College. Kahoot was utilised to provide an interactive experience for Years 10-12 girls who were tested on their general knowledge of material science, safety and the nature of work in the construction and engineering industry, while also hearing from female representatives from QQT's architect and structural engineers.

Figure 17 The first stage of the Jump Start program: A site tour hosted at QQT.

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4.4 Wellbeing, Workplace Health & Safety

The mental and physical wellbeing of project personnel is vital in maintaining the levels of safety on site as well as engagement and longevity of personnel. On QQT, we instigated several initiatives:

» Mental Health First Aid Training: nine mental health first aid trained workers on site act as a point of contact for an employee who has a mental health issue or is suffering emotional distress.

» Supporting initiatives from organisations including Mates in Construction and Foundation House, which focus on mental health of workers, and treatment of alcohol, drug and gambling addiction respectively.

» COVID-19 Measures: Multiplex initiated measures to protect the health and safety of workers and limit the spread of the virus:

- Staggered start times and lunch breaks to limit the worker numbers
- Enforcing social distancing at high-risk locations such as site entry, lifts etc
- Implementation of the Contact Harald Bluetooth card system that monitored worker proximity contact tracing purposes
- Proof of a negative COVID-19 result upon site induction to limit the spread of COVID-19 between different construction sites

» High-Risk Workshops: 190+ mandatory high risk workshops (HRW) were conducted prior to works being allowed to commence. The subcontractor responsible for the upcoming high risk works, explained the rationale for the upcoming activities to Multiplex senior management, the NSW Safety Group, relevant subcontractors and consultants and site team members. Safety risks were identified, carefully considered, then mitigated or resolved prior to works commencing.

» Physical Health: The QQT project encouraged improvement in physical health through:

- Weekly boot camps free of charge for Multiplex workers
- QQT team entering in social sports tournaments
- Annual skin checks for Multiplex workers

» Flexibility at Multiplex: In order to promote a work-life balance on the QQT project, the Multiplex site team members were entitled to rostered days off (RDO) each month in order to encourage flexibility in the workplace. Multiplex further encouraged a flexible workplace by implementing a "working from home" roster to reduce exposure time in the office, and therefore the likelihood of COVID-19 spreading in the workplace. In addition, by allowing staff to work from home, Multiplex staff members were able to successfully balance external commitments and their work schedule during the pandemic.

» Mates in Construction: Mates in Construction is a charity established to reduce the high level of suicide among Australian construction workers. Multiplex invited Mates in Construction to QQT to speak at several weekly site communication meetings in order to disseminate information regarding services that may assist workers who are struggling with their mental health.

Figure 18 Multiplex Mental Health first aiders training program