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Rocco Bressi is a structural engineering design manager for Bovis Lend Lease in Millers Point, Australia. Specializing in structures designed and constructed from reinforced concrete, post-tensioned concrete, and structural steel, Mr. Bressi has extensive experience in numerous building systems and construction techniques. At Bovis, he has been responsible for the detailed structural engineering design and documentation of many large-scale projects including retail centers, hotels, industrial facilities, and high-rise commercial developments.

At the Council on Tall Buildings and Urban Habitat's 6th World Congress in Melbourne, during February 2001, Mr. Bressi presented a technical paper on Aurora Place in Sydney, a commercial high-rise tower designed by architect Renzo Piano. This project was nominated as winner of the Institution of Engineers, Australia, 2001 Engineering Excellence Awards for Building Developments. For the 7th World Congress, Mr. Bressi will present a case study on the 126 Phillip Street high-rise project in Sydney, a development designed by architect Norman Foster.

He is a member of the Institution of Engineers in Australia and is a chartered professional engineer. Mr. Bressi earned both an honors degree and postgraduate diploma in structural engineering from the University of Sydney.

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## **126 Phillip Street, Sydney**

126 Phillip Street is a super premium office tower containing 31 commercial levels, newly completed on the corner of Phillip and Hunter streets in Sydney. With 462,850 square feet (43,000 square meters) of office space, it has commanding and unrestricted views of Sydney Harbor and the Botanical Gardens. It will be recognized by its distinctive architectural roof feature, adding to the city skyline on the eastern edge of the city.

Renowned for its creation of many international buildings, London-based Foster and Partners is the lead architectural firm responsible for the architectural design. Bovis Lend Lease is the project manager of design and construction, responsible for the detailed structural design of the building frame, detailed design and coordination of the lift frame, and design management of façade components and the building maintenance systems.

126 Phillip Street presents a new office typology for Australia through the combination of the three key building elements: core, atrium, and floor plate. This presentation will discuss structural aspects of each.

The first 24 office levels each measure 15,500 square feet (1,440 square meters) in area. The remaining floors range in size from 9,040 square feet (840 square meters) to 13,130 square feet (1,220 square meters) as they step in three level modules to form the basis for the tapering architectural roof feature that projects approximately 791 feet (241 meters) above the ground.

Paper prepared by

**Rocco Bressi**

For the

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Tower**



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# 126 Phillip Street, Sydney Commercial Office Tower

## SUMMARY – ABSTRACT

126 Phillip Street is a super premium office tower containing 31 commercial levels recently constructed on the corner of Phillip and Hunter Streets, Sydney for developers and owners Investa Property Group. With 43,000 square metres of net office space available, it will have commanding and unrestricted views of Sydney Harbour and the Botanical Gardens. It can be recognized by its distinctive architectural roof feature adding to the iconic city skyline extending along the eastern edge of the city.

Renowned for their creation of many international buildings, London based Foster and Partners are the lead architects responsible for the architectural design. They were assisted during the detailed design phase by Sydney based collaborating architect, Hassell.

Bovis Lend Lease is the project manager responsible for the design and construction of the entire development. In addition to the base building, Bovis Lend Lease was also responsible for the design and delivery of the integrated fitout for the major pre-commit anchor tenant Deutsche Bank and also for tenants Ebsworth & Ebsworth and Bain International.

The base building contract was awarded to Bovis Lend Lease for a sum of \$235m. This was supplemented by additional contracts worth in excess of \$40m for integrated fitouts.

Lend Lease **design** is responsible for carrying out the detailed structural design and documentation of the building frame, detailed design and coordination of the structural steel lift frame and architectural roof feature. Lend Lease **design** was also responsible for the design management of key façade components and the building maintenance systems utilising its highly specialised internal structural design resources.

126 Phillip Street presents a new office typology for Australia through the combination of the three key building elements: core, atrium and floor-plate.

In a departure from traditional office design; the core, containing fire stairs, toilets and all building service risers, is removed to the western exterior of the building, making it truly remote from the office floor plates.

Book-ended by the two concrete cores are parallel banks of glass lifts housing 16 passenger lifts that climb up and down within an exposed structural steel lift framework. The virtual perpetual motion created by the transparent lifts will attract interest in 126 Phillip Street 24 hours a day, both at ground level and across the city skyline.

At 160 metres tall, the atrium containing the passenger lifts provides a visual contrast from the office floor-plate and responds naturally to the environment. Daylight is drawn down through the building and relief air is strategically exhausted from the floor plates up through the atrium.

Connection floor plate bridges span each end of the atrium, from the lifts to the office floor-plates. These forum-sized walkways create reception and meeting areas immediately off the lift lobbies.

The typical floor plate has overall dimensions comprising 64.0 metres long in the north-south direction and clear spans 21.0 metres wide in the east-west direction. The tower columns are set on a 9.0 metre north-south grid that facilitates a façade and building-planning module of 1.5 metres in each direction.

To span effectively 21.0 metres in an east-west direction across the office floors, transverse post-tensioned beams have been proportioned to have a depth of 800 mm and a width of 900mm. The beams are notched to a depth of 400mm at their ends for a length of 2.0 metres. This facilitated the distribution and reticulation of above ceiling services and also enabled the beams to be post-tensioned directly from the previously constructed floor.

# 126 Phillip Street Commercial Office Tower

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## CONTENTS

PROJECT OVERVIEW .....	5
EVOLUTIONARY DESIGN .....	6
DESIGN AND PROJECT MANAGEMENT PROCESS .....	7
KEY MILESTONES.....	8
BASIC BUILDING STATISTICS.....	8
EXISTING SITE CONDITIONS AND DEMOLITION .....	9
SITE GEOLOGY AND FOUNDATIONS .....	9
STRUCTURAL DESIGN APPROACH OF THE BUILDING FRAME.....	10
STRUCTURAL DESIGN INITIATIVES .....	13
WIND ENGINEERING .....	14
STRUCTURAL ANALYSIS.....	15
CONCRETE QUALITY .....	17
ENVIRONMENTALLY SUSTAINABLE DESIGN AND ENERGY MODELING .....	17
ARCHITECTURAL ROOF FEATURE.....	20
BUILDING MAINTENANCE SYSTEMS.....	23
MECHANICAL SERVICE SYSTEMS (HVAC) .....	25
ATRIUM CFD ANALYSIS .....	26
FIRE ENGINEERING.....	28
FAÇADE SYSTEMS .....	29
LIFT SERVICES .....	32
PROJECT DESIGN TEAM.....	34

## PROJECT OVERVIEW

126 Phillip Street is a 31 level super premium office tower recently constructed on the corner of Phillip and Hunter Streets, Sydney. Located on the prime eastern edge of the Sydney's CBD district, 126 Phillip Street has commanding and unrestricted views of Sydney Harbour and the Botanical Gardens. Its distinctive roof feature adds to the iconic city skyline extending along the eastern edge of the city.

With 43,000 square metres of office space, the tower also offers street level retail facilities and underground car parking. It provides an exciting new covered plaza to be known as "The Assembly", an historical reference to a hotel that once stood on the site. This publicly accessible space, and a courtyard level "pocket park" provides tenants and their visitors a mix of interesting meeting places at the base of the tower.





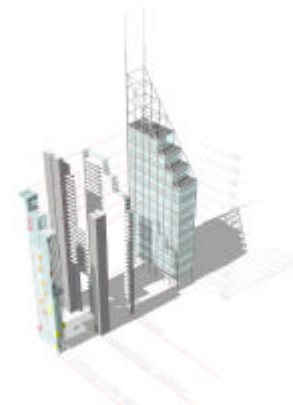
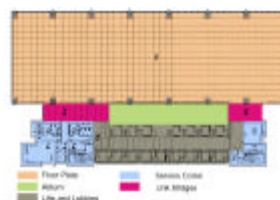
## EVOLUTIONARY DESIGN

126 Phillip Street presents a new high-rise office typology for Australia through the combination of the several technically innovative key building elements such as:

- **Offset service cores** - In a departure from traditional office design, the concrete cores, containing the fire stairs, toilets and risers, are offset to the western side of the building, making it the first high rise remote office core building in Australia. The re-location of the core allows an uninterrupted floor plate.
- **Column free floor-plates** – Measuring 21m wide by 64m wide the main commercial floor plates are only supported by perimeter columns set within the façade. This feature gives occupiers unlimited flexibility in terms of fitout and future business requirements. Tenant churn costs and times are significantly reduces with the building floor plates being designed to support raised computer floors throughout.
- **Atrium** – Positioned between the cantilevered concrete service cores and the floor-plate is the atrium, which at 160 metres high runs the full height of the building. Clad in performance glass, the atrium, combined with the building facades systems, it allows optimum natural light penetration to enter the building from every direction. The atrium is used environmentally as part of the building mechanical system and provides a managed path for the controlled extraction of heat and smoke from within the building during normal or emergency operating conditions.
- **Scenic lifts** – Set on the western facade, book ended between the cantilevered concrete service cores and free standing within the atrium space are 16 glass clad scenic passenger lifts. Comprising low, medium and high rises; they are installed and supported by an open structural steel cellular framework. The lift lobbies are joined to the sides of the concrete service cores from which access is provided onto the main floor plates by connecting bridges. The virtual perpetual motion created by the transparent lifts will attract interest in 126 Phillip Street 24 hours a day, both at ground level and across the city skyline.
- **Fire engineering approach** - Visual transparency through the atrium is enhanced by the fact that the supporting exposed cellular steelwork has been able to be retained without the need for the application of fire rated cladding protection. Extensive fire engineering modelling and rigorous evacuation procedures made way for more practical solutions.
- **Architectural roof feature** - Projecting in excess of 91 metres above the roof, it provides a structured iconic exoskeletal element that assists with the termination of the façade modulation and building form. The ARF gives the tower a unique and recognizable form in the city's skyline and balances the towers proportions especially the expansive eastern elevation when viewed from the Domain.

It provides shielding to the roof top plant and has integrated signage and lighting elements. The ARF is constructed from fabricated and painted mild steel plate of various thicknesses. It uses recessed bolted connections to hold the various members together. The tall masts are also fabricated with mild steel plate and are fitted with tuned chain dampers to negate the possibility of the resonance.

*Spatial arrangement of typical floor*



*Exploded view of building frame components*



## DESIGN AND PROJECT MANAGEMENT PROCESS

Vision and a daring to be different create projects like 126 Phillip Street. A team approach between all involved parties is essential. The current owners and developers of the property have been a pivotal link between the authorities, lead and collaborating architects, engineering and specialized consultants, project and design managers, construction team and tenants. With a commitment to the long term quality of the building the team has worked towards creating a nexus whereby all parties are in contact and understand the vast array of issues that arise during the development of such a unique project.

A team approach was the basis for enabling Bovis Lend Lease to negotiate a project management role for design and construction services with the client provided significant hurdles could be met. The client approached Bovis Lend Lease early in 2001, after the Stage 1 DA design (essentially a building envelope criteria) was deemed not financially viable.

Bovis Lend Lease in cooperation with London based architect, Norman Foster, then developed a Stage 2 DA design to meet strict performance, financial and aesthetic criteria set by the client's brief and bounding authority requirements. To maintain market confidentiality during this period, Bovis Lend Lease relied on engineering design input from its internal specialists within Lend Lease design. Key to making the client's and architect's vision possible was the development of a simplified structural building frame, lift support frame and architectural roof feature for the proposed off set core building.

The hurdles to be overcome before the client would commit to Bovis Lease Lend to proceed with the delivery of the project were as follows:

- Stage 2 DA Approval to be on terms acceptable to the client
- Foster and Partners to sign off on the design initiatives and cost plan proposed by Bovis Lend Lease and agree to complete the project
- Achievement of minimum NLA targets
- Agreement of a Guaranteed Maximum Price contract value for the design and construction
- Assist the client to secure a pre-committed anchor tenant
- Confirmation of a contract programme that would achieve the anchor tenant's occupancy requirements
- Complete all of the above targets in time to receive vacant possession of the site
- The existing sites to be cleared by the authorities as having any significant archaeological relevance that may hinder the development

These issues were all successfully resolved resulting in a contract being signed with Bovis Lend Lease in August 2002, after which time demolition and construction was able to commence for almost a three year journey until practical completion of the base building including the integrated fitout requirements of Deutsche Bank.

Renowned for their creation of many international buildings, London-based Foster and Partners supported its commitment to their first project in Sydney with the relocation of key personnel to oversee the architectural design of the development.

All other consultants were engaged locally to best facilitate and optimise the detailed design and delivery of the project with input from key subcontractors and suppliers.

ProjectWeb, an Internet based project management tool developed by Bovis Lend Lease, was used by all participating team members for the management of all correspondence and documentation of the project.

The project management process adopted by BLL ensured that the development responded to the Clients brief and was delivered safely, on time, on budget and with the highest level of quality. The high level of collaboration between the client, project managers, construction managers, designers, cost planners and specialist contractors paved the way for success.

Throughout the various design and construction phases of the development formal and informal workshops, design working groups and design approval group, project control group sessions were held on a regular basis with the appropriate stakeholders ensuring that the objectives of the development were achieved and expectations met.

Although the process was structured it was flexible enough to ensure that changes to the brief could be adopted, including integrated tenancies that required major changes to the structure and services of the tower. The project management philosophy adopted by BLL was instrumental in leasing 85% of the commercial tower space prior to the date of practical completion.

## KEY MILESTONES

The key project milestones achieved by the project team are summarised below:

May 2001 – Design development deed signed

- Dec 2001 – Deutsche Bank pre-committed to 40% of the commercial lease area
- Dec 2001 – Stage 2 DA lodged
- April 2002 – Stage 2 DA approved
- July 2002 – Vacant possession
- August 2002 – Demolition commenced
- April 2003 – Structure commenced
- September 2004 - Floor-plates completed
- July 2005 – Building completed
- September 2005 – Integrated fitout completed and occupation

## BASIC BUILDING STATISTICS

The following statistics summarise some of the key features of the commercial tower:

- Number of commercial levels – 31
- Dedicated plant levels – Levels 35, 36 and 37
- Number of basement levels – 2
- Number of basement car parks - 78 and 15 vehicular service bays
- Number of lifts – 16 scenic lifts (in 6 LR, 5 MR and 5 HR configuration) plus one service lift
- Floor to floor height of commercial floors - 4000mm
- Main floor plate dimensions – 21 metres clear span by 64 metres long
- Main floor, ceiling and façade planning grid – 1500mm each way
- Ceiling height to office levels – 2850mm with an allowance for 150mm raised access floor
- Approximate GFA 49000 square metres
- Approximate NLA commercial floor 42500 square metres – 1,400 for Levels 4 to 27, 1,200 for Levels 28 to 30, 1,000 for Levels 31 to 33 and 800 for Level 34
- Core areas (square metres) – 354 Levels B2 to 27, 324 Levels 28 to 40
- Overall building height (to top of masts of ARF) – 240 metres
- Core slenderness ratio (height/depth) - 21
- Maximum lateral east-west sway movements – 300mm
- Tower building frame lowest natural frequency – 0.18 hertz
- Stability frame – Limited shear wall outriggers action at Level 35 to 37 but the building stability mainly relies on the combined frame action of the cores, floors and columns
- Average overall axial shortening of tower frame due to creep and shrinkage – 75mm
- Volume of concrete used – 35,000 cubic metres
- Tonnes of reinforcement used – 6,200 tonnes
- Tonnes of post-tensioning used – 350 tonnes
- Tonnes of structural steel used for the ARF and the scenic lift frame grillage – 1250 tonnes
- Overall construction time including design and site demolition – 4 years
- Base building construction cost \$235 million

## EXISTING SITE CONDITIONS AND DEMOLITION

Like most central city business district developments, projects like 126 Phillip Street usually involve the need for consolidation of land that often requires demolition work. For this development four commercial buildings and a ground level open car park were amalgamated yielding an area of 3,935 square metres.



*Site location plan*

*View of existing building prior to demolition*



De-building works in a developed city environment is almost synonymous with tall building projects and is often complex requiring protection to the surrounding environs. Often it requires the removal of noxious, deleterious and contaminated materials.

The site to be cleared involved the "de-building" of reinforced concrete framed buildings comprising of 19, 17, 16 and 9 levels including the basements. The existing buildings were completed from a period dating from 1930 to the 1970's.

Obtaining information about the existing buildings is often difficult and requires a significant level of exploratory work to analyse and understand the structures to be demolished.

During the six-month demolition process and in line with the project's total environment commitment, the deconstruction of the existing buildings on the development site removed 35,000 tonnes of waste of which over 92 per cent was recycled, 32 per cent above the legislative requirement for waste minimisation.

The materials to be recovered were treated as follows:

- Concrete and Brick - Taken to a recycling facility for crushing and screening to produce alternatives to quarry products.
- Timber - Removed offsite, denailed and resold as used or recycled timber.
- Carpets - Some carpet was reused on site to seal off the scaffold catch decks during demolition works. Once the scaffold was stripped the carpet was removed to landfill.
- Metal - Taken to scrap metal yards for recycling and or resale.

## SITE GEOLOGY AND FOUNDATIONS

Reference to the Sydney 1:100,000 Geological Series Sheet indicates that the site is underlain by the Hawkesbury Sandstone of Triassic Age, close to the boundary with the Ashfield Shale.

As previously constructed commercial buildings containing between one and four levels of basements formerly occupied the site it had been previously partially excavated. The proposed development required that the whole of the excavation be extended into the Hawkesbury Sandstone by approximately 11 metres across the whole of the site to create two levels for basement carparking, truck service docks, substations, lift pits and plantrooms.

The major geotechnical issues at this site were:

- Excavatability of the sandstone
- Ground generated vibrations during excavation exacerbating adjoining buildings
- Seepage requiring dewatering
- Induced rock stress relief
- Underpinning of existing buildings located on or close to the boundaries of the excavation
- Shoring of the upper levels of the excavation faces, together with rock bolting and shotcreting of the lower zones of fragmented rock or extremely weathered rock
- Capacity of the rock exposed at the base of bulk excavation for the support of the major structural foundation loadings

Maximum tower column working loads are in the order of 45,000kN and are supported on reinforced pad footings founded onto Class II and III sandstone having design bearing pressures varying between 3.0mPa to 6.0mPa as recommended by the geotechnical investigation work carried out by Coffey Geosciences Pty Ltd.

The offset north and south cores have a total working load in the order of 450,000kN and 300,000kN respectively and are supported on 1.5 metre thick rectangular core rafts set flush with the western boundary and projecting 1.5 metres on their other three sides beyond the main load bearing walls to assist with load dispersion to the sandstone bedrock. To limit and control the core raft differential settlements and rotations each of the cores are permanently anchored to the sandstone bedrock. The core anchors also assist in controlling the north and south core verticality. This was essential for maintaining final installation tolerances of the structural steel lift frame.



*Raft excavation of south core*

A total of 13 permanent anchors were used to laterally restrain the cores. Eight anchors contained 47 x 15.2mm diameter strands and 5 anchors contained 22 x 15.2mm diameter strands. The anchors were stressed through the 1.5 metre thick core rafts into the sandstone bedrock below and locked off at 60% of their ultimate strength.

Connecting the south and north cores and a 600mm thick raft was used to support the exposed structural steel lift frame. This raft is founded onto a slightly weaker sandstone stratum than the main north and south service cores to deliberately tune the settlements of each raft.

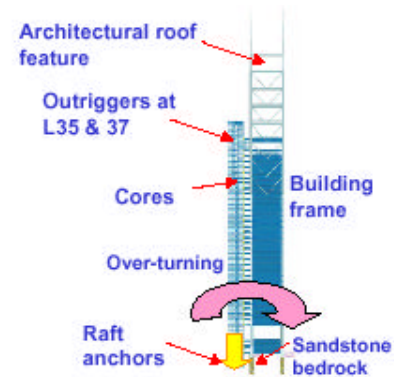
## **STRUCTURAL DESIGN APPROACH OF THE BUILDING FRAME**

The building frame for the tower comprises of several components. Lateral stability is developed by the moment resisting frame that is formed by linking the off-set and anchored cantilevered concrete cores with the concrete frame formed by the tower columns and floor plates. The structural steel lift frame relies on the concrete frame for its stability and is attached at each level to restrict the horizontal movements whilst facilitating its vertical movements by guided Teflon coated bearing surfaces.

The eccentric nature of the building frame has provided significant structural analysis challenges to the designers along with the understanding of the time dependent differential movements between the concrete elements and the lift frame.

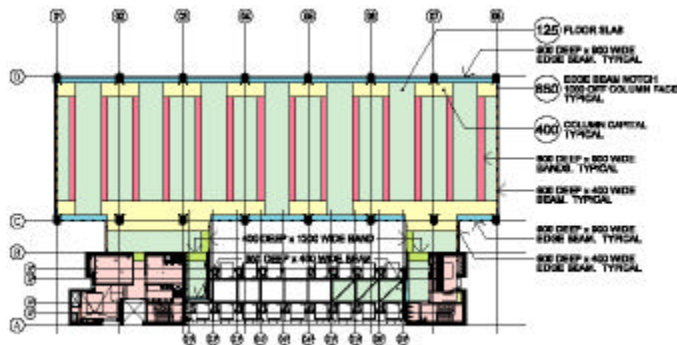
The building frame efficiency was optimized by extensive finite element sensitivity studies of structural analysis models containing various configurations of all of the structural components.

Combining the actions of a regular moment resisting frame and the cantilevered action of anchored and reinforced concrete cores, the lateral stability and sway of the overall building frame has been resolved by linking these two elements with the connecting bridges at each level and by providing additional shear wall outrigger links located between the eastern side of the core walls and the tower columns within the high level plant rooms and the roof at Level 37. The location and form of the outrigger linking systems adopted have enhanced the tuning of the stiffness characteristics generated by the core and the moment resisting frame and provided the acceptable limits required to be met for sway deflections and accelerations.



*Principle structural frame actions*

The typical floor plate has overall dimensions comprising 64.0 metres long in its north south longitudinal direction by 21.0 metres wide in its east west transverse direction. The tower columns are set on a 9.0 metre north-south grid that facilitates a façade and building-planning module of 1.5 metres in each direction.



*Arrangement of typical floor structural components*



*Typical floor formwork table arrangement*

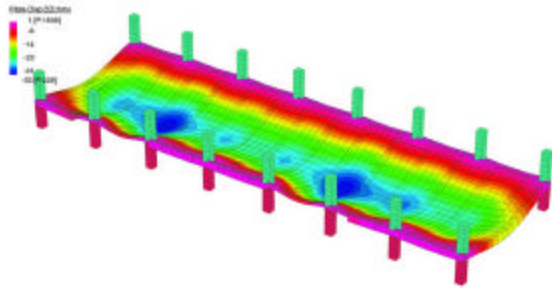
To span effectively 21.0 metres in an east-west direction across the office floors, the transverse post-tensioned beams have been proportioned to have a depth of 800 mm and a width of 900mm. The beams are notched to a depth of 400mm at their ends for a length of 2.0 metres. This facilitates the distribution and reticulation of above ceiling services and also enables the beams to be post-tensioned directly from the previously constructed floor. The floor beams are located at 4.5 metre centres and are offset from the transverse column gridlines by 2.25 metres. The 125mm reinforced slabs spanning one way between the beams acts as flanges for the beams. This thickness also corresponds closely with that required to achieve a 2-hour fire resistance floor rating. The slabs act integrally with the beams to provide a combined T-beam action, therefore, enhancing their overall stiffness.

The post-tensioned floor beams develop rotational end stiffness by utilising the torsional stiffness of the edge beams and the tower column framing. They contain 4 profiled flat-ducted cables. Within each cable duct 5 x 15.7mm diameter super-grade, low relaxation strands have been placed. All anchorages for the strands are accessed from the notches provided to the underside of the beams.

This eliminates the need to provide scaffolding and site access beyond the perimeter of the floor plate. It also eliminates the potential clash of façade support brackets supported close to the edge beam faces.



*Typical floor deflection diagram*



the location of the link bridges the longitudinal edge beams have been reduced in depth to 400mm to allow the passage of services from the cores to the floor.

To keep the dimensions of the columns to a minimum and consistent throughout the tower levels, up to 100Mpa high strength concrete has been specified. Typically, the tower columns have dimensions of 1000mm wide by 1400mm long. The columns are integrally engaged with the floor plate by 900mm (the same width as the edge beams). The remainder of the column section projects outside the floor plate to suit the architectural profile of the facade. Throughout the 15.3 metre height of the lobby, the tower columns have been increased marginally in size to prevent lateral buckling. The basement columns are rectangular in form measuring 1800mm long by 1200mm wide.

All tower columns have been founded on sandstone bedrock utilising recommended foundation design bearing pressures of up to 6.0mPa.



*View of concrete building frame from the western atrium*

The two cores containing primarily the egress stairs, on floor plantrooms, toilets and major risers are also constructed from reinforced concrete. The external walls are nominally 500mm thick, except for the eastern wall, which is designed to be 600mm thick, and the internal walls 250mm thick. Main riser shafts are also constructed integrally with the cores and provide structural stiffening for the perimeter walls and support for the core infill slabs. Both concrete cores are supported directly from the sandstone bedrock using a 1500mm thick concrete raft. The raft is permanently anchored to the bedrock to counteract any resultant tensions that may develop from lateral wind loads, seismic loads combined with eccentric gravity loads.

Various linking options between the cores and the moment resisting tower building frame have been considered and analysed. However, using the proportions of the principle members as described above initial calculations showed theoretically that pin connected link bridges at each level are sufficient to distribute the applied forces and control lateral movements and accelerations to an acceptable level. This aspect of the building design has been extensively analysed during the Design Development and Detailed Design Stages.

As can be seen by the final framing plans the bridge links can be made simply by a flexible slab coupled to the side of the moment resisting frame and the cores. These types of structures also facilitated the proposed construction methodology. The building frame and the cores were able to be constructed independently followed through by the link slabs.

The three-dimensional exposed structural steel grillage frame supporting the lift shafts and atrium lobbies have been designed to be connected to the north and south cores for their lateral stability.

Each lift cell has been consistently proportioned to provide for ease of repetition in detailing, fabrication and erection.

Obviously, substantial coordination and interaction between the architect, structural engineer, façade subcontractor and lift subcontractor has been essential to resolve the final detailing of the exposed framework.



*View of lift frame grillage from the atrium*



*View of lift frame grillage from Phillip Street*

Similarly, the cantilevered exo-skeleton architectural roof feature framing and masts that extend beyond Level 37 and each stepped roof level have also been fabricated from structural steel and then erected in a pre-finished state. A more detailed commentary regarding the architectural roof feature design and construction can be found later within the paper.

The typical floor plates are designed to ensure that there are only slight perceptible vibrations under footfall drop heel effects, or from other internal or external sources. To determine floor vibrations, reference has been made to the ASCE paper by Thomas M Murray 1995, "Building Movements" for acceptable design methods and criteria. Structure vibrations are designed such that the harmonic movements or responses of the building components are not resonant with their own natural frequencies.

The structural components, particularly the floor beams are designed to limit their deflections under service loads within acceptable limits and consideration for:

- Structural integrity
- Visual appearance
- Avoidance of excessive floor slopes
- Prevention of cracking in floors, walls and ceilings
- Proper installation and operation of equipment
- Traffic loadings
- Building tenancy requirements
- Avoidance of roof ponding

## **STRUCTURAL DESIGN INITIATIVES**

From a structural engineering viewpoint design opportunities have arisen as the construction methodology and the architectural fabric of the building was developed. The structure was designed to allow the offsite prefabrication of many components. This initiative assisted with the time and quality of construction. The adopted structural systems have made it possible to design the following elements with the advantages gained by offsite factory prefabrication:

- Column reinforcement cages
- Footing reinforcement cages
- Edge beam reinforcement cages with facade support brackets



- Floor beam reinforcement cages and post-tensioning cables
- Core wall penetration boxes
- Egress stairs and handrails
- Tailored fabric slab reinforcement
- Structural steel lift and shaft framing
- Structural steel to the architectural roof feature and mast framing



*Sample prefabricated typical floor beam cage*

*Prefabricated column cages*



## WIND ENGINEERING

A 1/400 scale model of the proposed 126 Phillip Street development was tested in a simulated boundary layer of the natural wind over suburban terrain to enable determination of design pressures for the façade cladding and canopies.

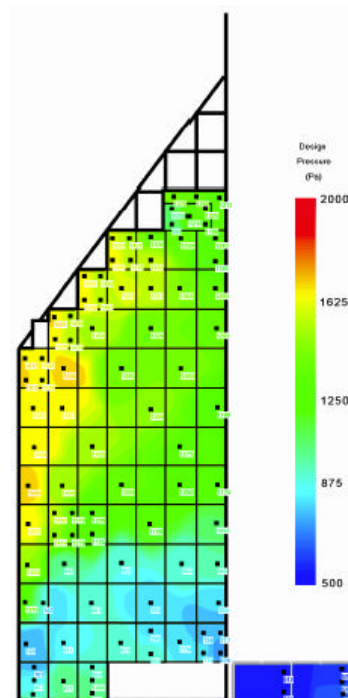


*Façade pressure model*

Surface pressures on the façades were measured with reference to the free stream static pressure for 72 wind directions at 5 ° intervals. Some differential pressures across the wall partition on the ground level were also measured with reference to the pressure directly behind the measurement location.

The pressure data was normalized with the free stream mean wind speed at the height of the top of the building (160m) and processed as mean, standard deviation, minimum and maximum pressure coefficients.

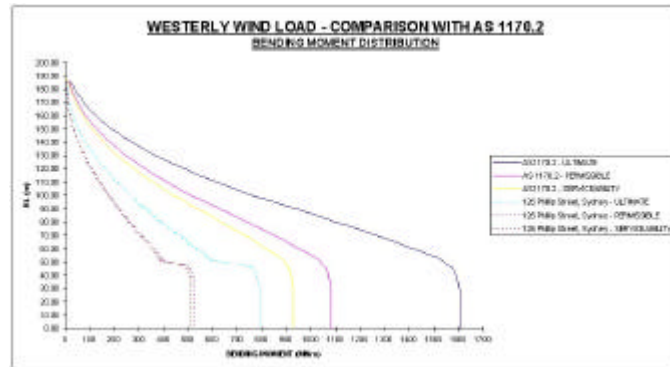
Permissible stress design pressures were determined using directional wind speed data for Sydney and summary figures of the highest design pressures, with an allowance for internal pressure for an effectively sealed building were provided as basic façade surface pressures. These design pressures were based on a 50 year return period 3 second mean gust wind speed for use with the permissible stress design approach and the SAA Glass Installation Code AS1288.



*Easter façade wind pressure results*

Wind tunnel tests were also conducted on an aeroelastic model in a natural wind boundary layer model, to determine the dynamic response of the tower due to wind action. Mean and standard deviation moments for the tower were measured and presented in coefficient form as a function of damping, wind speed and wind direction with the tower in the existing Sydney city environment.

These results enable the structural engineers to confirm the over turning design moments, shear force distributions and serviceability accelerations.

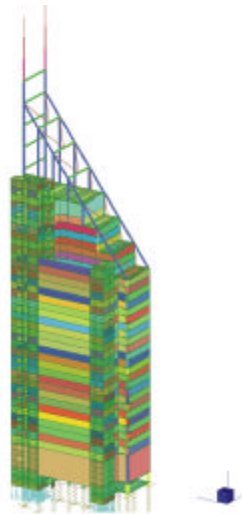


*Comparison of wind generated bending moments*

## STRUCTURAL ANALYSIS

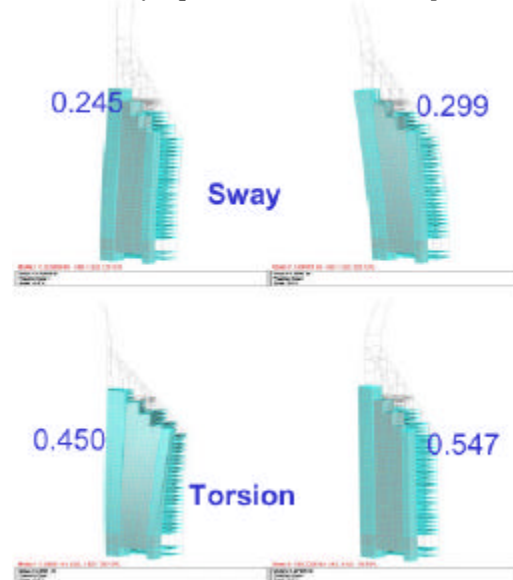
Bovis Lend Lease structural engineers used Strand7 finite element program to perform numerous structural analyses on the building frame of the commercial tower.

A rigorous structural analysis of the tower building frame was carried out to comply with Clause 7.8 of AS3600, Concrete Structures Code. The analysis of the building frame takes into account the relevant material properties, geometric effects, three-dimensional effects and interaction with the foundations. The principal aim of the analysis was to effectively predict the structural behaviour of the unique



*Strand 7 finite element structural analysis model*

*Natural frequencies and modal shapes*



shape of the tower frame subjected to various static and dynamic loading conditions. These loading conditions were generated from combinations of superimposed dead loads, live loads, wind loads and seismic loads.

Static load combinations complying with the relevant Australian Standards provided realistic predictions of the actions of the building frame, particularly due to applied lateral loads and eccentric gravity loads.

The dynamic response of the structure also needed to be assessed to evaluate the natural frequencies of the tower frame and consequently the response of the structure in terms of perceptible building accelerations.

A finite element linear buckling analysis enabled the determination of the tower column effective lengths, which then assisted with their final detailed design.

A suitable mesh grading to model the floor in plate elements was developed. Five plate element properties were used per level to account for the end notching of the beams and slab thickenings adjacent the core. Strand7 allowed the use of different membrane and bending thicknesses for each plate property. Beam elements were used to model the perimeter beams. The self-weight of the structure could be determined by assigning plate densities. Superimposed floor loads and live loads were applied as face pressures to plate elements.

Plate elements were used to simulate the façade of the building. The façade plate elements were a Quad4 Plate/Shell type, each node connected to the structural beam elements. The lateral wind pressures were then applied to the face of these plate elements.

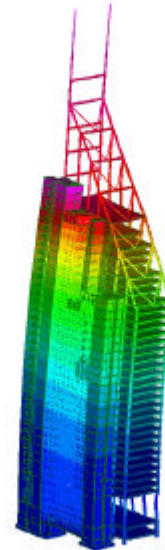
The linear static, non-linear static, natural frequency and linear buckling solvers were used to evaluate the structural behaviour of the tower frame. Linear static analyses were used to predict the structural behaviour of the structural elements for a combination of lateral loads and eccentric vertical loads.

The moment distribution of the lateral load between the core and the frame was also evaluated. It was important that a sensitivity analysis be carried out to account for the varying stiffness of the slab-core and slab-column connection.

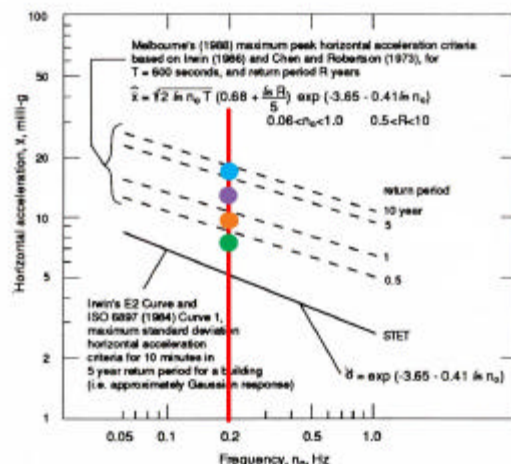
The sub-modelling feature in Strand7 was used to study the detailed actions of the structural components in critical areas. This was achieved by using a much finer mesh in these areas compared to the coarser mesh of the global model. The sub-modelling feature allowed the bending moments, shear forces and axial forces to be found for the subsequent design of each structural component using the results of the global model.

A sensitivity analysis was also performed on the model by varying the dynamic and static moduli of the structural sections. This enabled the range of possible natural frequencies for the tower to be determined.

The occupancy comfort was gauged by a study on the accelerations of the building under dynamic loading conditions. For the lowest natural frequency, the calculated building frame accelerations were compared to maximum peak recommended values for a mean wind return period of 0.5, 1, 5 and 10 years as set out by AS1170 Part 2, Wind Loading code.



*Lateral deflection of building frame*



*Building accelerations for occupancy comforts*

The base finite element model has the following statistics:

Number of nodes	57,440
Number of beam elements	12,461
Number of plate elements	49,538
Number of equations	344,494

The model was run in excess of 160 times to evaluate the sensitivity and effect of different structural parameters relating to the building frame.

## CONCRETE QUALITY

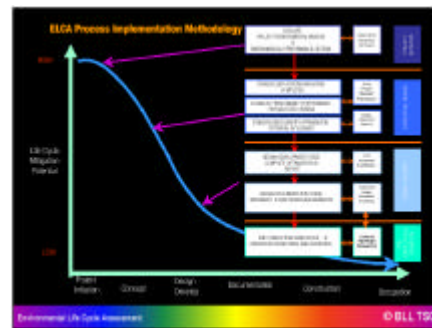
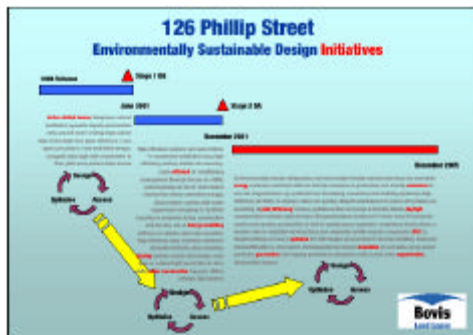
For the project, the specified concrete 28-day strengths varied between 25mPa and 100mPa. High performance concrete was used to control long-term differential elastic axial shortening, shrinkage and creep between the columns and core walls. All concrete mixes were super-plasticised and the maximum 56-day shrinkage was limited to 600 micro-strain.

By way of trying to equate the overall axial elastic shortening, shrinkage and creep between the core and tower columns, the concrete shrinkage specified for the concrete used in the columns was limited to 450 micro-strain compared to 600 micro-strain used for the core.

## ENVIRONMENTALLY SUSTAINABLE DESIGN AND ENERGY MODELING

126 Phillip Street has been designed and built in full contemplation of the ecologically sustainable design objectives of the project's key stakeholders. The process of assessment and measurement was transparent, involved key stakeholders and had an inherent rigorous reporting regime. It guided design decisions to optimize the eventual outcome for environmental, economic and social aspects using a "Design, Assess, Optimize" approach.

### *Environmental sustainable design initiatives process*



### *ELCA processing implementation methodology*

This has resulted in an extensive whole building energy modeling study to be carried out to assess the energy consumption for the proposed office development. It included the energy modeling of the typical office floors, impacts of core areas, lift lobbies, and the atrium. The results from the modeling were used to assist with the selection and optimization of service and plant systems for the efficient operation of the building.

To determine the energy consumption for the project at various design stages the validation protocol and metrics used were in accordance with SEDA's Australian Building Greenhouse Rating (ABGR) scheme. After ongoing evaluation the building achieved a 4.2 star ABGR with an aspiration to reach a 4.5 star ABGR following on from the completion of tenant fitouts and occupation when actual energy usage can be more accurately determined and measured.

The consideration of environmentally sustainable design was based on a building development that minimised the economic, environmental and social impacts over the life of the project that included the phases of demolition, design, construction, and operational and potential reuse. The SEDA rating or the ongoing energy consumption was only one aspect of this evaluation.

From a design discipline perspective some of the key features that were considered and adopted to provide beneficial sustainable design initiatives can be summarised as follows:

#### Architectural

- *Orientation of the building to minimise external heat loads*
- *Remote core building design provides a high level of shading from afternoon sun*
- *Large vision glass panels provide high levels of natural light*
- *Large column free floor plate encourages favourable working environment and future tenant flexibility and building adaptability*
- *Raised floor and dedicated service zones within the ceiling space to facilitate tenant fitout adaptability*
- *Provision for internal blinds to facilitate glare control*
- *Atrium space used as a buffer zone to heat transmission and solar radiation from the west façade to floor the plates*
- *Streetscape canopies and trees to mitigate environmental wind conditions for pedestrians*

#### Mechanical

- *Tenant flexibility and zoning achieved by the installation of floor-by-floor chilled water air handling plant*
- *High level of floor zoning with individual control VAV units*
- *Optimisation of the on-floor air handling plant using static pressure reset controls of the air handling plant*
- *Variable speed drives on fans and pumps to facilitate part load operation.*
- *Computerised building management and control system incorporating plant optimisation such as condenser water temperature reset*
- *Running plant using outside air economy cycles*
- *Provision of relief air paths from the occupied commercial floors to the Atrium space. Further heat and smoke control of the atrium by fan assistance but can be naturally ventilated under favourable external wind pressure conditions.*
- *High efficiency chiller plant and motors*
- *Engineered chilled water temperature differentials to optimise water-pumping energy*
- *After hours and low traffic floor operation CO monitoring of the basement carpark and loading dock ventilation system*
- *High efficiency air filters to enhance indoor air quality*

#### Electrical

- *Maximise light fixture spacing to ensure minimum lighting load of 400 lux*
- *Design of air conditioning system using realistic lighting loads in lieu of a maximum specified constant*
- *Consolidation and reduction of submain reticulation throughout the building to minimise embodied energy*
- *Use of electronic ballasts in lieu of iron core ballasts to tenant area lighting to minimise embodied energy and increase efficiency*
- *Installation of motion detectors for BMCS control of house lighting areas*
- *Energy metering at main switchboards for power usage and consumption*

#### Hydraulic

- *Dual flush cisterns (3/6 litre flush)*
- *Flow restrictors to basin tapware*
- *Pre-heating of cold water supply to the Domestic Hot Water from the condenser water system heat exchanger*



- *Utilise mechanical space heating water from the central plant in lieu of dedicated domestic hot water plant*
- *Utilisation of polypropylene piping in lieu of copper*
- *Gravity feed of cold water supply from roof level storage tanks*
- *Stormwater reuse for the operation of the Assembly water feature and wash down operations*

#### Fire Services

- *All water consumption utilised for testing purposes of pumps is recycled*
- *Utilisation of photo-optical detectors in lieu of ionisation detectors*

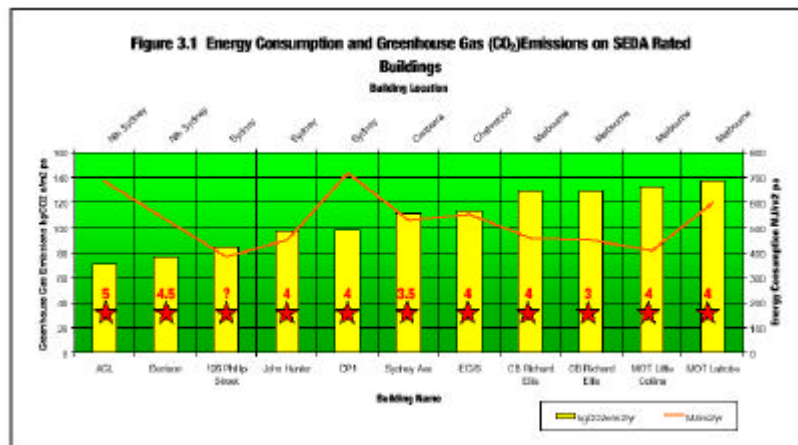
#### Structural

- *Post tensioned concrete building frame reduces depth of structural components therefore reducing floor to floor height and maximising available floor to ceiling height*
- *Where practical concrete mixes contain a percentage of fly ash as a means to reduce cement content*
- *Individual coring and testing underneath each major footing to enhance the available rock bearing pressure thus minimising rock excavation and the use of concrete to foundations*
- *Use of high strength concrete mixes to minimise size and maximise strength of structural elements particularly tower columns*
- *Use of long length bars in the columns and in the floor beams to minimise lapped reinforcement splices*
- *Off site factory prefabrication tower columns and floor beams to minimise site labour and material wastage*
- *Purpose designed re-usable typical floor table forms and core jump form system for the construction of the floors and cores*
- *Use of standard rolled formed I-sections for the lift framing to optimise structural capacity and minimise fabrication and wastage*
- *Construction of prototype lift cells and jiggling to review and optimise fabrication techniques*
- *High level of design resolution, coordination, design documentation and design led shop drawings enabling efficient construction processes and planning to occur*
- *Development of a unique core to slab coupler connection system eliminating core wall penetration block outs and site waste*

#### Façade

- *Adoption of energy efficient façade systems using high shading coefficient and U-values to minimise heat loads but maximise light transmission*
- *Use of insulation materials behind non-vision panels and composite aluminium sandwich cladding materials for chevron sections to provide higher levels of insulation to floor plates*
- *Aluminium used in extrusions incorporates a percentage of recycled content*
- *Pallets for delivery are recycled*
- *Completion of comprehensive aero-elastic modelling and façade pressure testing of the building to provide realistic design pressures for the facade and structural design*

Preliminary overall energy performance and greenhouse gas emission performance modeling based on the above initiatives indicate an annual base building operational energy usage of approximately 385MJ/m<sup>2</sup>/yr, with a greenhouse rating of less than 85kgCO<sub>2</sub> e/m<sup>2</sup>/yr<sup>1</sup>. These figures suggest that the building will be at the forefront of sustainable design for comparable premium grade commercial office buildings with respect to energy consumption and greenhouse emissions.



*Comparison of energy consumption and greenhouse gas emission on SEDA rated buildings*

## ARCHITECTURAL ROOF FEATURE

Being one of the last major structural components required to be assembled on site, the design of the architectural roof feature was required to respond to the many constraints imposed by the architecture, approving authorities, buildability and maintenance requirements. The key constraints were governed by the:

- Building grid and the façade geometric forms, properties and overall member sizes
- Planning constraints such as building height restrictions, sun axis planes, overshadowing
- Coordination and consistency of finish and colour to match the aluminium façade chevrons
- Unobtrusive or 'invisible' structural connections
- Accessibility for maintenance and the support of specialist lighting
- Environmental conditions and suitable corrosion protection systems
- Wind, thermal and transient loading conditions
- Lightning protection and earthing requirements
- Structural integrity and serviceability
- Dynamic response
- Fabrication techniques and erection methodologies
- Cost and time factors

The finalisation of the design was an iterative process between the client, designers, authorities and subcontractors that needed to consider all of the design input criteria and constraints.





*North view of architectural roof feature*

Simplistically, the ARF feature constructed from fabricated mild steel plate of various thicknesses in an open lattice arrangement set by a grid pattern 9m wide and 12m high. The fabricated steelwork hexagonal and triangular box section members and cylindrical masts to the top of the building are primarily architectural in that they complete a façade pattern on the building extending about 91m above the concrete roof level of the building and to an overall height of 240m above ground level.

Recessed and end plated bolted connections are used to hold the various members together.

The tall masts are also fabricated with mild steel plate and are fitted with chain dampers to negate the possibility of the masts resonating with wind-induced motions.

Due to the unusual architectural and structural form of this building element it was a client requirement that the final design be independently reviewed.

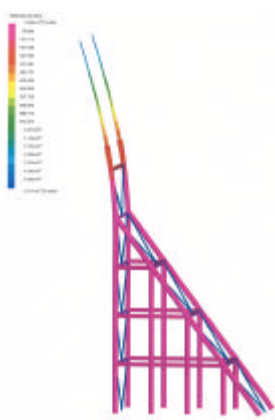
The structure is accessible only by maintenance workers and does not incorporate any heavy equipment.

The primary loads on the structure are gravity loads and lateral wind loads with subsequent over turning moments. The gravity loads have been calculated from geometric properties of the elements and steel density. The architectural roof feature has a painted external finish with no additional cladding loads.

The design ultimate limit state wind speed at the top of the ARF has been calculated using the results from wind tunnel tests. The wind speed has been based upon a return period of 1000 years and has been calculated for the most severe cardinal directions. This has been conservatively used in the design, irrespective of wind direction.

The lateral wind loads have been calculated using Australian Standard AS1170.2 (2002) for Wind Actions with a suitable aerodynamic shape factor and dynamic response co-efficient. There was little influence from dynamic factors with the response co-efficient equal to 1.00.

The use of aerodynamic shape factors for the determination of the wind load is appropriate despite the relatively large member width(s). This is due to the individual members being long with aspect ratios (length/width) greater than 8.



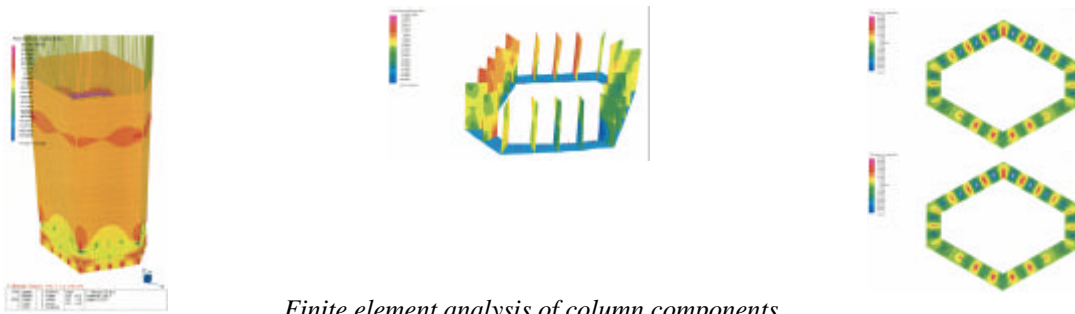
*Deflection diagram of architectural roof feature*

The wind load on multiple open frames can be reduced on second and subsequent frames due to the influence of shielding by the first members. The amount of shielding is related to the solidity of the first element and the spacing of the elements, with closely spaced more solid elements having greater shielding than more open widely spaced elements. As the architectural roof feature comprises of relatively open and widely spaced elements the influence of shielding has not been included which is appropriate.

The load combinations examined in the model analysis are in accordance with AS 1170.0 (2002) with a variety of different wind directions examined combined with the applied dead load.

The structural analysis was performed on a desktop computer using a proprietary finite element package Strand7. The software package is used worldwide and is recognised in the industry as providing accurate results. A number of different finite element models were developed using either plate or beam elements.

The plate elements selected were 10 layer isotropic shell elements with elastic plastic material properties for the steel. All the major structural elements including main plates, longitudinal stiffeners and end plate stiffeners were modelled allowing the determination of the individual stresses.



*Finite element analysis of column components*

The supports for the architectural roof feature were modelled as pinned to reflect the possible lack of end fixity. Using a significant number of plate layers can increase the accuracy of the model with an improved calculation of through thickness bending effects and elastic-plastic response.

The overall member dimensions in the ARF have been sized architecturally to achieve the desired statement. However the plate thicknesses have been selected to simplify construction and ensure an economical structure. Internal longitudinal and lateral stiffeners have been provided to increase the effective sectional properties of the thinner elements. Normal strength steel plate and standard plate thicknesses have been used throughout the structure whenever possible.

The capacity of the members has been determined using Australian Standard AS 4100 (1998) for Steel Structures and general engineering principles.



*Fabrication of column components*



*Architectural roof feature frame erection*



*Erection planning model of architectural roof feature*

The structure has been broken into a number of smaller repeating modular elements to simplify manufacture and aid in construction. These elements include K-Joints, T-Joints, X Joints and straight members. At the joints, the plates are fully welded to ensure adequate transmission of force through the element. The typical connection detail from the joints to the straight member uses recessed end plates and high strength tensioned bolts.

Tall cylindrical masts have a propensity to vibrate due to their inherent size, slenderness and construction. This vibration occurs when wind flowing around the mast cause shedding vortices, which coincide with the natural frequency of the mast resulting in a phenomenon, called "lock in". On inadequately damped structures this can result in relatively large cross-wind vibrations. As this phenomenon can take place at frequent low wind speeds the member can be subjected to a large number of cycles in a short time period. To eliminate this behaviour the structural damping of the system must be increased, often with the inclusion of a chain mass damper.

The natural frequencies of the mast and structure have been determined and are appropriate for the member size and structural scale. The first seven modes of vibration occur below 2 Hz.

The inclusion of a chain mass damper at the top of each mast is warranted as the masts could experience wind-induced vibration at a variety of different wind speeds. The hanging chain mass dampers will increase the structural damping of the masts such that wind induced vibrations are unlikely to occur.

To ensure that the members subjected to cyclical loading do not fail prematurely, either the applied stress must be reduced and/or alternatively the number of stress cycles is reduced. Australian Standard AS 4100 (1998) provides guidance on the calculation of the maximum service stress allowable for an associated number of cycles. The code also provides a cut off stress limit, with values below this being relatively unaffected by the number of cycles.

The finite element model has been used to review the applied plate stresses in the structure under service loading. These stresses are within the cut-off limit specified in AS 4100 (1998) indicating that consideration for cumulative damage does not need to be considered.

High strength tension friction bolts have been specified for the major steel connections. This connection minimises the slippage that can occur especially for cyclically loaded details.

The individual plate elements forming the perimeter of the closed box sections and the cylindrical mast are connected with full penetration butt welds, category structural purpose. Although a stringent testing procedure is required for this weld class and category, it is appropriate for the structure, its importance and location. For members with cyclical loading structural purpose welds are used throughout. However for members not subjected to cyclical loading, more economical general purpose welds have been used.

Corrosion protection to the external surfaces of the ARF has been provided by applied coating systems having a minimum durability (coating life to first major maintenance) of 25 years as defined by AS/NZS 2312, System Designation PUR5. The coatings consist of a three-coat sprayed paint system applied to a Class 2.5 abrasively blasted surface. The first two coats used are polyamine air cured epoxies and the top coat aliphatic acrylic polyurethane.

The end plates of the connecting members seal off the internal surfaces of the tubular sections and consequently no corrosion protection was deemed to be necessary for these surfaces.

Miscellaneous items such as bolts, access grating and ladders were specified to be hot dipped galvanized.

The architectural roof feature at 126 Phillip St Sydney is a significant element of architectural steelwork. It comprises of approximately 220 tonnes of painted structural steelwork and a structure of this type has created some unusual challenges from a design, fabrication and erection perspective.

*Erection of north western mast*

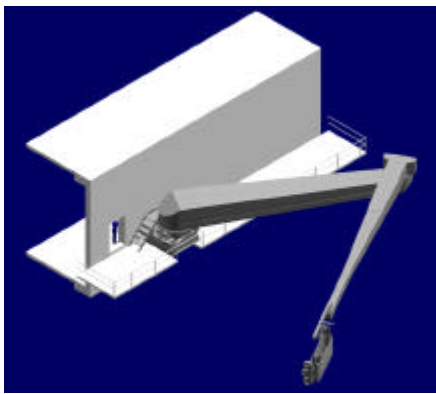


## **BUILDING MAINTENANCE SYSTEMS**

The tower form changes both internally and externally particularly above Level 28 to respond with the set sun axis planes and surrounding overshadowing easements limits. The resulting stepped and articulated shape of the building has provided the project design team with a series of challenging building maintenance solutions. External façade access is also exacerbated by the interference of the exposed framing of the architectural roof feature.

To clean and maintain the external façade surfaces of the building three building maintenance units have been installed:

- The pedestal-mounted unit supported on the roof of the north core at Level 40 is a counter balanced and rotating double slew jib machine having a jib span of 16 metres.
- The unit on Level 37 is supported from a set of parallel tracking universal beam rails located close to the perimeter of the floor. This unit slews and luffs to access the façade beyond the architectural roof feature framing. It is also designed to access and maintain the dedicated signage zones on the eastern elevation.
- The third and largest external unit is supported directly from the building frame on the southern elevation of Level 35. A 2.0 metre diameter and 800mm long cylindrical stiffened hub is encased into the side of the reinforced deep beam-wall that spans 21 metres across the end of the double height plant room floors set between Level 35 to Level 37. The hub is then used to fix the slew ring housing from which triple horizontal slew arms are cantilevered to reach in excess of 31 metres beyond the stepped floors at Level 28. This unit is not counterbalanced and relies on the structure mass for its stability.



*Schematic design model of slew arm unit fixed at Level 35*



*Encased hub for BMS unit at Level 35*



*Fully extended slew arm jibs of BMS unit at Level 35*



*Pedestal mounted BMS unit at Level 40*

The main structural components of all of the external units have been hot-dipped galvanized and then coated with an appropriate protective architectural paint system. Whilst operating, the machines have been designed to sustain loads generated by permissible wind speeds of 25m/s.

Each of the external units is fitted with a 3.0 metre long two-man access cradle having a safe working load of 250kg. In addition to the safe working load of the cages, each jib will have the capacity to carry the working load of the heaviest glazing unit for its respective elevation, including associated lifting frame and winch. The cradles house all of the controls for the operation of the units. The

access cradles are fitted with a needle jib head allowing the cages to be swivelled around for more accurate control. This feature maximises access around the architectural roof feature columns and its diagonal beam elements.

Typically, from each access cradle conventional rope restraints can be fitted to the façade mullions at 12 metre maximum centres. Additional soft rope restraints can be used to assist with the safe manoeuvre and traversing of the cradles about the stepped and articulated building facades.

The access cradles are generally constructed from aluminum and always remain attached to the jibs of the unit. Within each cradle a GPO is provided rated suitable for the operation of small hand tools.

The internal façade surfaces of the atrium containing the steel grillage support frame for the high-speed scenic lifts are accessed by rail systems suspended from the underside of the glazed sky light roof framing at Levels 28 and 37. The roof of the each lift cars also provides a platform for access to the adjacent steel frame, the internal surfaces of the western facade and the core cladding.

In those areas where machine access was not possible, supplementary catwalk and rope access systems have been installed to facilitate abseiling procedures. These systems are effectively utilised on the architectural roof feature where access is required to all components of the exoskeletal frame including the very top of the masts approximately 240 metres above street level.

The installed building maintenance systems have the capacity to safely clean the whole of the exterior and interior façade surfaces of the building up to six times a year during normal working hours.

## **MECHANICAL SERVICE SYSTEMS (HVAC)**

The primary HVAC system is a floor-by-floor VAV system with a central air handling unit serving a portion of the high-rise floors. The VAV system serves the office floor plates, with fan coil units serving the lift lobbies. The ground floor lift lobby is served by a low level system. Return air is drawn back to the air handling unit by the supply fans via the return air plenum for floor-by-floor air handling unit s. The central air handling unit serving Levels 28 to 34 uses a return air fan.

The atrium is indirectly conditioned with relief air from plenums at each floor. Relief air openings between the plenums and atrium are operated based on outdoor air economizer operation. Relief Air fans within the atrium remove air from the atrium and are modulated based on outdoor air economizer operation.

A central plant system consisting of water-cooled chillers and boilers serve the air conditioning system with heat rejection of the chiller plant via roof mounted cooling towers. The office temperature is maintained during occupied hours, at  $22.5 \pm 1.5^{\circ}\text{C}$ . Space temperature floats during unoccupied hours.

Design parameters used for the HVAC system are as follows:

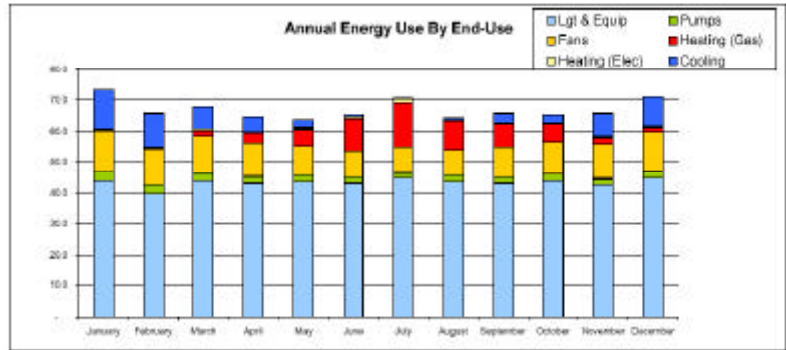
<b>Design Parameter</b>	<b>Operational Design Base Case</b>
External temperature	34 degree centigrade dry bulb
Occupancy	10 square metres/person
Lighting	8.5 watts/square metre
Equipment	35 watts/square metre

The VAV systems are floor by floor with Levels 4 to 27 served by two air handling units per floor as follows:



- The northern air handling unit has two primary supply ducts each with a zone heating and cooling coil, they serve the northern and eastern perimeter zones.
- The southern air handling unit has three primary ducts serving the southern, western and central area zones.
- A floor-by-floor air handling unit serves Levels 28-34 in the northern core and a central southern air handling unit located in the Level 35 plantroom.
- Zoning is based on the mechanical design perimeter zones having a depth of 4.0m.

The air handling unit supply fan variable speed drives are controlled to maintain a constant duct static pressure. The air handling unit supply fans start at 7:00am to pre-condition the space prior to the majority of occupants arriving at 8:00am. During unoccupied hours, the systems are not allowed on regardless of space conditions. When conditions are favorable, duct static pressure reset is utilized to minimize the energy consumed in these periods of low load.



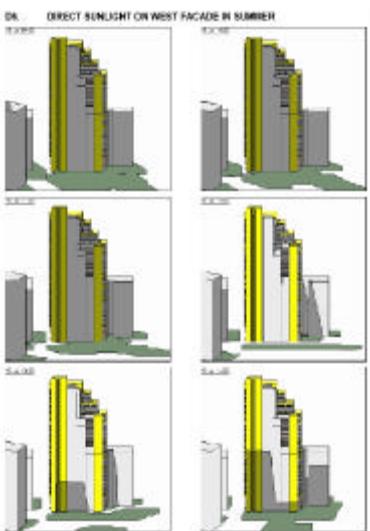
*Monthly energy consumption model*

The outdoor air dampers are controlled from a dry bulb economiser that allows 100% outdoor air for economy cycle cooling when outdoor conditions are favourable. The economizer is enabled when ambient temperature is below 21°C and any zone temperature is greater than 22.5°C. The economizer modulates from a minimum of 40% to 100% to maintain the lowest of the required supply air temperature set points.

## ATRIUM CFD ANALYSIS

The atrium space on the western side of the building has an overall width of approximately 16 metres. It is 31 metres long on the north-south axis of the building, commencing at the ground floor lobby and terminating at Level 37 nearly 160 metres in height. It contains all of the scenic lifts and commercial floor lobbies.

As the atrium faces due west, extensive sun shading diagrams were prepared and review with sun angle diagrams. Both sets of these diagrams showed that at times the atrium was substantially sunlit and that shading from adjacent buildings was minimal.



*Sun shadow diagrams on western façade*



*Sample sunlight penetration into lobby zone*

In view of this, and the lightweight construction of the atrium space that is substantially formed of steel and glass, no allowance was made for any shading or thermal storage, and the radiation loads were based on the full incident solar radiation. The only exception to this was the 15 metre high glazing to the entry foyer that, because of its low position, was considered to be totally shaded throughout the day.

To evaluate human comfort conditions within the atrium subjected to radiant heat from the sun, extensive computational fluid dynamic (CFD) sensitivity studies were undertaken of the lift lobby areas and the interconnected atrium spaces in order to determine their climatic and thermal conditions, air velocities and pressure distributions under a range of design variables and options.

The initial series of CFD studies performed were primarily used to determine the best method of conditioning the ground floor entry foyer and lift lobbies whilst resolving the following key issues:

- The impact on the atrium conditions of varying the performance of the atrium west glass
- The likely after-hours condition with various ventilation scenarios
- The optimization of the summer time operation to limit the peak internal temperatures
- The typical winter condition
- The peak conditions likely to be experienced under extreme ambient conditions

The total air mass balanced flow in the atrium space could be influenced by incorporating methods to provide supply or exhaust air that could be either forced flowed or introduced by natural ventilation depending on the thermal scenario being considered. To assist with the varying conditions within the atrium space the following initiatives have been implemented in the project:

- High rise exhaust fan at Level 36
- Mid-rise exhaust fan at Level 19;
- Entry foyer makes up louvres;
- Atrium west high-rise relief air shaft
- Relief of conditioned air from the floors
- Ground floor lobby air conditioning via slotted floor vents
- Air leakage via the revolving entry doors.

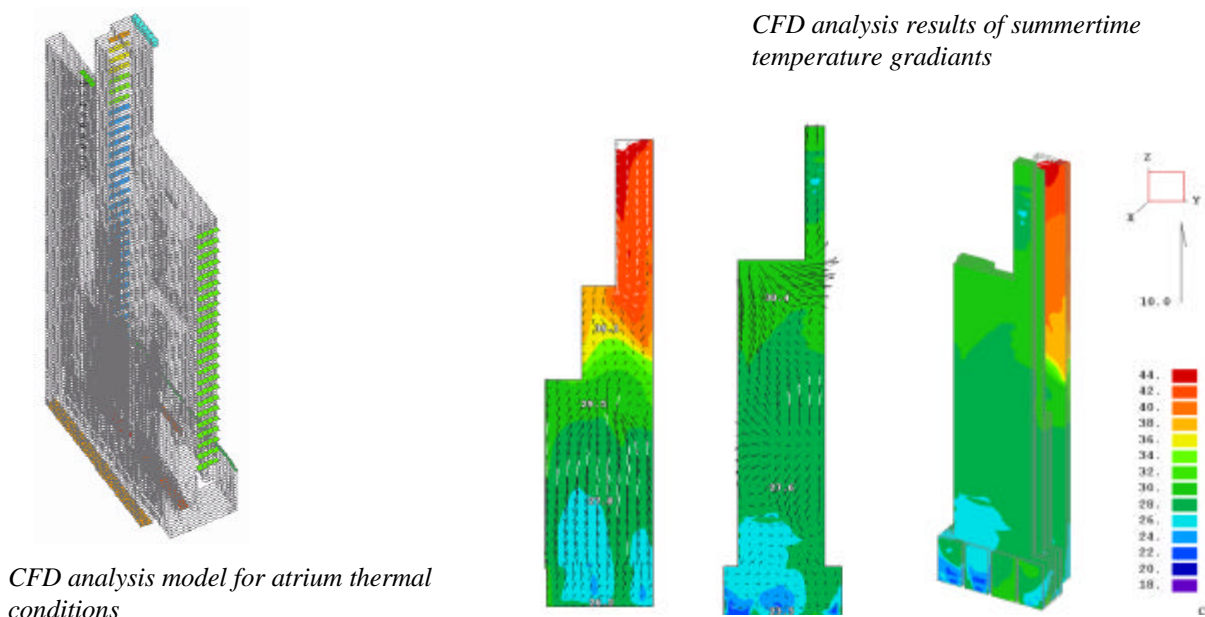
The key findings of these CFD studies showed that the atrium space required some intervention to achieve optimal operating conditions for different times of the year. These findings and recommendations can be summarized as follows:

- A connection was required between the west side of the atrium and the east of the atrium at high level in order to prevent full compartmentalization between the lift lobbies. This helps to vent and limit the temperatures on the internal space closest to the west facade.
- Discharging the relief air from the office floor into the western portion of the atrium reduced the temperature within this zone, and limited the temperature variation across the atrium.
- Improving the performance of the atrium west glass façade from a shade coefficient of 0.52, to 0.39 reduced the peak summer time atrium temperature by approximately 3 – 4 degrees centigrade.
- When an atrium west glass with a shade coefficient of 0.39 is used, the predicted peak summer time atrium temperature falls generally within the range of 29 to 33 degrees centigrade.
- Under peak summertime weekend conditions, when using an atrium west glass with a shade coefficient of 0.52, the peak temperatures are predicted to be in the order of 42 degrees, when the atrium is naturally ventilated. Improving the performance of the atrium west façade glass will reduce the peak temperature.
- Under winter operating conditions, the large volume of relief air that passes through the atrium limits the temperature variation throughout the atrium. Under these conditions, the pressure variation in the atrium east side is also limited to less than 20 Pa (+12 to – 3)



- The automatic control of the atrium ventilation will only be implemented when the building is unoccupied, and the air conditioning plant is off. Temperature sensors located at the high points of the atrium and connected to the BMCS, will sense the internal temperature and initiate automatic control under a staged program.

The calculated temperature results within the atrium obtained from the CFD analyses we also used to simulate thermal gradients over the full height of the exposed lift framing. Temperature changes or gradients within the atrium were directly related to possible movements in the lift framing. The principle actions of concern from a structural engineering viewpoint were the vertical differential axial shortening caused between the concrete cores and the steel lift framing. The estimated possible movements required that the lift frames closest to the cores be installed so that they could freely move in a vertical orientation.



## FIRE ENGINEERING

An extensive fire safety engineering assessment was undertaken of the project to verify possible alternate solutions to meet the Performance Requirements of the Building Code of Australia. Areas that were investigated covered the following aspects of the building design:

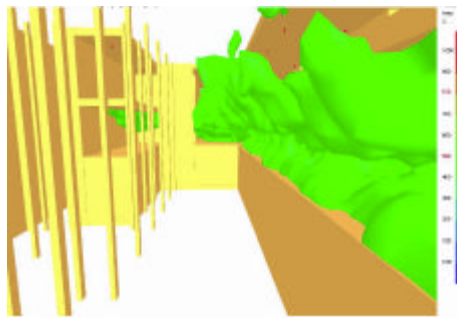
- Structural fire resistance and compartmentalization
- Egress
- Services and equipment
- Atrium provisions

Some of the major beneficial outcomes resulting from the alternate solutions can be summarized as follows:

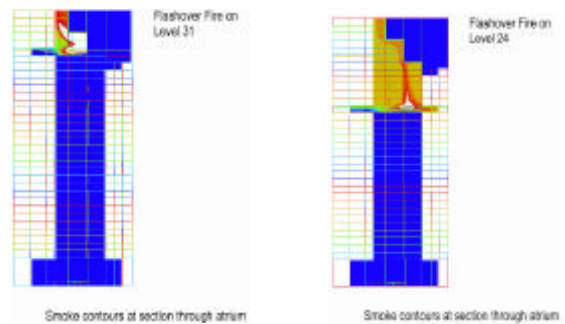
- Reduction of fire ratings of primary structural components having regard to brigade intervention and sprinkler activation.
- Structural lift framing members within the atrium were constructed in non fire-rated steel as the framing components were located a significant distance from the fire load sources on the floors. A sensitivity analysis using CFD was been undertaken to analyze the performance of the unprotected structural steel in the event of a flashover fire on one floor of the building where there is an inter-connection between two consecutive floors. The bottom floor of this inter-connection is also involved in the flashover fire. The sprinklers on the fire floor were assumed to be valved off, whereas the sprinklers on the floor above were assumed to operate. The project structural engineer analyzed the resulting temperatures of the columns under the assessed fire scenario, confirming that the steel members and corresponding

connections were capable of resisting the applied loadings under the nominated heat exposure condition.

- Planning strategies to enable inter-connecting tenant stairs to be opened over consecutive floors. Dedicated single tenancy stairs connecting up to 10 floors have been already installed.
- Tenancy layout options were enhanced on the large, column free, typical open floor plates due to the flexibility of egress travel distances being able to exceed 40 metres.
- Elimination of sprinklers and reduction of smoke detection requirements to the undercroft area of the ground floor “Assembly” installed with 14 m ceiling. This is based on the open nature of the undercroft and analysis of reasonable worst case fire scenarios in this area.
- Smoke detection was not provided within the upper levels of the atrium due to sufficient detectors on each of the typical floors and flame detectors covering fire sources within the lobby area.
- Atrium bounding construction designed on a performance basis thereby eliminating the need for wetting sprinklers on the sides of the atrium glazing. Based on analysis of worst-case fire scenario, smoke spilling into the atrium managed by a single exhaust fan linked with zone pressurization and sufficient time for evacuation from the uppermost floors.
- Smoke exhaust quantities within the atrium determined on a performance basis as the smoke spilling into atrium is managed by the installed exhaust systems, thereby enabling the atrium to be used as a smoke relief path.



*Sample fire engineering model on typical floor adjacent to atrium*



*Various smoke contours through atrium*

## FAÇADE SYSTEMS

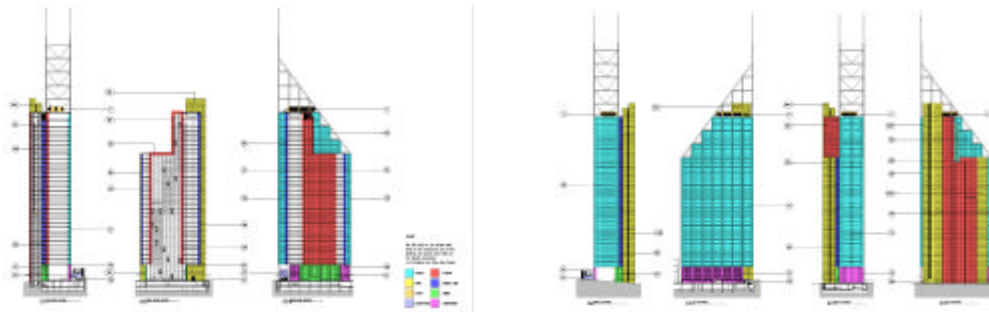
The installed aluminium and glass curtain wall systems spans from floor to floor and are supported by the edge beams with cast-in anchorage brackets or from the horizontal transoms of the atrium lift framing. The panelised glazed façade systems are designed to cope with the anticipated building movements determined by structural modelling.

Each internal and external elevation of the building was specifically designed to meet performance criteria set by the client, architect, service engineers and the authorities. In all cases the design intent was to provide a high degree of visibility from the street level into the building without compromising the occupancy comfort.

Within the commercial floors, the façade and ceiling planning module used throughout the building was 1500mm in each direction. The façade panels were factory made to match this module and the typical floor-to-floor height of 4.0m. The western façade of the atrium and the lobby glazing were subdivided vertically to suit the lift installation and the supporting structural steel grillage framing. The panels were mostly double glazed to achieve stringent heat transmission and acoustic performance, however, single glazing was deemed to be more appropriate for the western façade of the atrium.



*Diagrams showing different  
façade types used to clad building  
frame*



The vision glass was for each façade type selected to meet the following performance criteria:

- **Solar control** was required to minimize solar heat gain through the glass on the facades. A shading coefficient was selected in accordance with the design parameters for the air conditioning system and to ensure a satisfactory level of occupancy comfort. Lowering internal roller blinds installed on the eastern and northern elevations when necessary can provide additional solar control.
- **Visible light transmission** through the vision glass was limited to reduce the risk of excessive glare. A visible light transmission level was selected in order to strike a balance between desirable perimeter day lighting and glare control. Internal roller blinds installed on the eastern and northern elevations can be lowered during periods of direct solar light penetration into the perimeter zones.
- **Thermal insulation (U-value)** was selected in order to limit conduction of heat through the glass that complied with the requirements of the air conditioning system.
- **Reflectivity** - The architectural intent and authority requirements for each façade was to create a low-reflectance appearance to the vision glass. External visible reflectance was selected to create the required low-reflectance appearance. Internal visible reflectance was limited to permit clear viewing from within the office space in low daylight conditions.
- **Colour** of the vision glass units was required be neutral in accordance with the architectural intent.

Due to desired aesthetic and architectural intent, supplemented by the need to ensure that the technical, fabrication and installation requirements of the building envelope could be achieved several different façade typologies were developed for each of the key elements and elevations including:

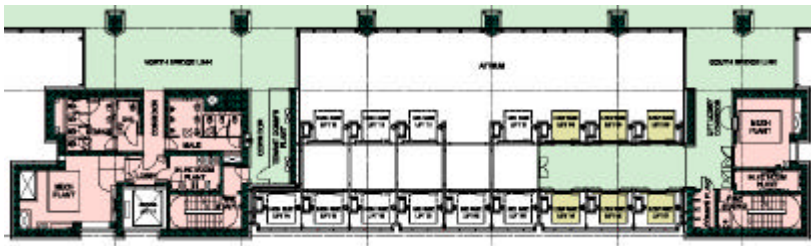
- Tower facades
- Atrium facades and roofs
- Core cladding
- Glazing to lift lobbies
- Ground plane main lobby glazing
- Glazed canopies and balustrades



## LIFT SERVICES

The main passenger lifts are arranged in two parallel banks that are orientated north south along the Phillip Street frontage. Passenger lift service is provided to all commercial floors of the tower via three separate banks serving Low Rise (Levels 3 to 16), Medium Rise (Levels 15 to 24) and High Rise (Levels 24-34). Six lifts service the low rise floors, with 5 in each bank for the medium and high rise floors.

The lifts themselves travel up and down the building within the open atrium space, supported by a three-dimensional cellular grillage framework of structural steel. The lift installation is unique as it is not housed within any solid or walled lift shaft in the conventional manner except within the open steel framework and lobbies at each floor served that are enclosed on both sides by floor to ceiling glass walls.



*Plan arrangement of service cores and lifts*

The lift cars themselves incorporate a high level of internal and external finish quality. Car walls are finished with opaque colour backed glass to all faces excepting the rear walls to those cars rising on the Phillip Street elevation. These cars have a clear glass, floor to ceiling panel that provides for unique passenger views out of the cars as they travels up and down within the building.

All cars incorporate appropriate disability design components including a separate dedicated car operating panel, specialised floor and control button indicators providing Braille and tactile indication to all car operating panels, visual and audible arrival signal mechanisms for each floor and internal handrails.

The main tower passenger lift service incorporates a high level of operational performance. The lifts combine optimum speed performance with extremely smooth acceleration and deceleration to provide passengers with a comfortable and efficient ride.

The lifts are designed with the following passenger capacities and speeds across the three rises:

- Low Rise 25 Passengers at 6.0m/s
- Medium Rise 25 Passengers at 7.0m/s
- High Rise 25 Passengers at 7.0m/s

During peak times the lifts are designed to move a minimum of 13.5% of the design population of each of the rises within the building up from lobby level in any five-minute period.

This lifting capacity provides the performance to achieve an average maximum waiting time interval from the lobby in peak periods of:

- Low Rise 28 Seconds
- Medium Rise 28 Seconds
- High Rise 30 Seconds

The basement loading dock and carpark levels are serviced by two conventional dedicated passenger lifts. These lifts are provided with a similar high level of appointment as the passenger cars servicing the main tower.

A dedicated goods lift is also provided to serve from the lowest basement level to level 35.



The major operational characteristics of the passenger lift service are summarised in the table below:

Lift Rise	Passenger Low Rise	Passenger Mid Rise	Passenger High Rise
Number Of Lifts	6	5	5
Floors Serviced	Ground to 15	Ground an 15 to 24	Ground and 24 to 34
Capacity	<b>1700kg</b>	<b>1700kg</b>	<b>1700kg</b>
Speed	<b>6.0m/s</b>	7.0m/s	7.0m/s
Handling Capacity (%)	>or=13.5%	>or=13.5%	>or=13.5%
Waiting Interval	< or = 28 secs	< or = 28 secs	< or = 30 secs
Car Size	<b>25 persons</b>	<b>25 persons</b>	<b>25 persons</b>
Door Opening (WxH) nominal dimensions	1.2 x 2.4	1.2 x 2.4	1.2 x 2.4



*View of partially erected lift frame*

## PROJECT DESIGN TEAM

### ***Client and Developer***

Investa Property Group

### ***Tenants***

Deutsche Bank (Anchor tenant)  
Ebsworth & Ebsworth  
Bain International  
Investa Property Group  
Allens Arthur Robinson

### ***Project Management and Construction***

Bovis Lend Lease  
Colin Ging and Partners (Representing the client)

### ***Lead Architect***

Foster and Partners London

### ***Collaborating Architect***

Hassell

### ***Urban Planning***

JBA Urban Planning

### ***Structural Engineering***

Lend Lease **design**

### ***Façade Engineering***

Arup Façades  
G James Glass (Main building facades)  
AGP (Lift frame glazing)  
Ascurco (Core cladding)

### ***Building Maintenance Systems***

Lend Lease **design**  
Farra Access Equipment New Zealand

### ***Wind Engineering***

Mel Consultants Pty Ltd – Professor Bill Melbourne

### ***Geotechnical Engineering***

Coffey Geosciences

### ***Mechanical Engineering***

Norman Disney Young

### ***Energy Modeling***

Arup

### ***Electrical Engineering and Security***

Norman Disney Young

### ***Lifts***

Norman Disney Young  
Otis

### ***Fire Engineering***

Stephen Grubits & Associates

### ***BCA Consultants***

Mackenzie Group

### ***Acoustics***

Acoustic Logic

### ***Hydraulic Designers***

LHO

### ***Fire and Sprinklers***

Warren Smith and Partners

### ***Quantity Surveyor***

Rider Hunt

### ***Cost Planning***

Bovis Lend Lease

### ***Structural Steel Fabrication***

3D Acudraft (Shop drawings)  
Nepean (Lift framing)  
Intercon (Architectural roof feature)  
C&V Engineering (Misc metalwork)

### ***Photography***

Martin van der Val