Title:	**Advances in the Structural Design of High-Rise Residential Buildings in Australia**
Author:	Owen Martin, Connell Mott MacDonald
Subject:	Structural Engineering
Keyword:	Structure
Publication Date:	2007
Original Publication:	CTBUH 2005 7th World Congress, New York
Paper Type:	1. **Book chapter/Part chapter** 2. Journal paper 3. Conference proceeding 4. Unpublished conference paper 5. Magazine article 6. Unpublished

Owen Martin, FIE Aust
Connell Mott MacDonald

Owen Martin is director of Connell Wagner and a board member of Connell Mott MacDonald's global building engineering business. His extensive experience and most recognized skills include advance structural design and analysis of wind sensitive, long-span, cable, and architectural structures; dynamics; and structural engineering of high-rise buildings.

Mr. Martin is one of Australia's leading tall building designers and has been involved in all three of Australia's current 85-plus-story buildings, including World Tower and Eureka. He pioneered the use of outriggers in Australian residential buildings on the Avillion Hotel and further developed and refined this system on World Tower.

He has personally led the structural design of a large number of concrete high-rise buildings in Australia ranging from 40 to 85 stories in height.

Advances in the Structural Design of High-Rise Residential Buildings in Australia

Connell Mott MacDonald has designed numerous tall buildings in various parts of the world and has advanced the state of the art in recent times in Australia. This presentation is based on a paper by the presenter and Brian Dean, principal at Connell Mott MacDonald, and will refer to experience gained from World Tower (85 stories, 853 feet/260 meters high), Eureka Tower (90 stories, 894 feet/300 meters high), Avillin Hotel (55 stories, 541 feet/165 meters high), and others. These buildings are all slender (up to h/b = 9) and residential, and contain many innovations in the area of structural engineering.

In particular, this presentation will examine advances in analysis techniques, structural systems (including post-tensioned outriggers), concrete strength and technology (particularly as it relates to stiffness and shortening), and structural systems. Results of monitoring of behavior (sway and shortening) will be presented and discussed. A specific research study was conducted in conjunction with the concrete industry to examine and monitor the creep properties and behavior of very high strength concrete (15,000 psi/100 MPa cylinder strength). The results of this will be summarized.

The use of special detailing (jacking and release) to avoid permanent dead-load transfer into wind elements (outriggers and sloping columns) will be of particular interest. This deals with the difficult problem of differential shortening between columns and core which are connected by outriggers.

In conclusion, the presentation will contribute to the state-of-the-art knowledge in our industry in tall concrete buildings around the world.

Advances in the Structural Design of High Rise Residential Buildings in Australia

Owen Martin[1], Principal
Brian Dean[2,] Principal
CTBUH Member
Connell Mott MacDonald
116 Military Road, Neutral Bay NSW 2089, AUSTRALIA
Tel: 612 94655599 Fax: 612 94655598
e-mail: martino@conwag.com

Abstract
This paper examines developments in the structural design of high rise concrete residential buildings in Australia's two major cities, Sydney and Melbourne. Reference is made to four projects where the use of reinforced and post tensioned outriggers in various configurations has been successfully implemented. The 90 storey Eureka Tower project, soon to be completed incorporates a liquid mass damper.

Keywords: Outrigger, high-rise, concrete, damper.

INTRODUCTION

The four projects, which are used to illustrate the developments in tall/slender concrete buildings are summarised below:

Table 1. Four Tall Building Projects

Building	Storeys	Height	Slenderness (h/b)	Frequency	Column Concrete Strength (Cylinder)	Wind Structure	Other
Hordern Towers	55	165	6	.18Hz	60MPa	Reinforced concrete outrigger & shear wall	
The Aston	30	90	7	.31Hz	60MPa	Offset outriggers	
World Tower	85	260m	9	.17Hz	90 MPa	Post tensioned concrete outriggers	
Eureka	90	300m	7	.17Hz	100MPa	Concrete shear walls	Liquid Damper at roof level

HORDERN TOWERS

The 55 level Hordern Towers project is 165m high with a slender basic width of 29m. At the base of the building the core is only 9m wide and for the upper 30 levels is only 5m wide. The 400mm thick, 9m deep reinforced concrete outriggers rigidly link the core to columns at the Level 23 plant room levels.

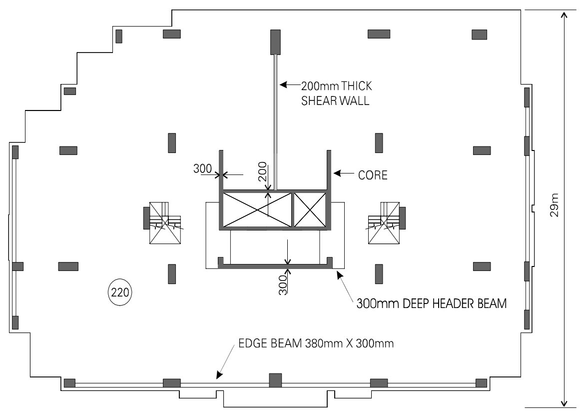

Fig. 1   Typical Tower Floor

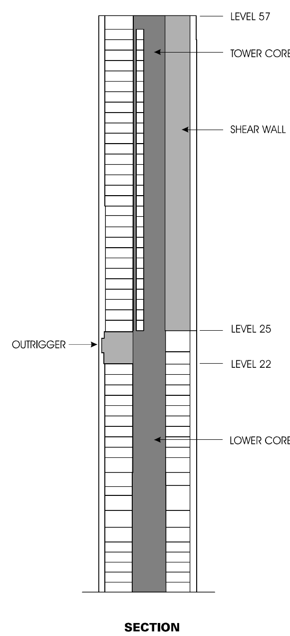

Fig. 3 - Section

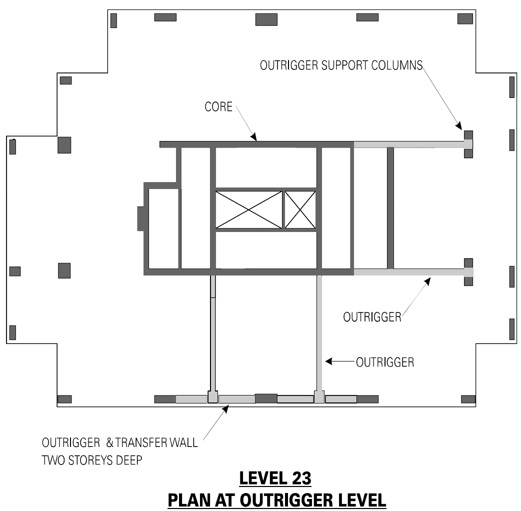

Fig. 2 - Plan at Outrigger Level

The outriggers significantly reduce the bending actions in the core such that wall thickness and reinforcement are not unduly penalised. In fact the core takes only 50% of the overturning moment in bending. Wall thicknesses of the core at the base of the building are 500mm for perimeter walls and 200mm for all other walls.

In the upper levels the core is further assisted by a single shear wall constructed between units to connect the core to the facade.

A relatively simple solution to deal with differential shortening was developed which sees the outriggers connected to the columns by flat-jacks which are inflated with hydraulic fluid. Thus they remain effective in resisting lateral load whilst allowing any residual stress carried by differential movement to be released periodically. Monitoring of creep movements was carried out and the final connection of the outriggers to the columns was carried out when movements were minimal some 3 years after commencement. This has been a most successful solution.

THE ASTON

An interesting building, the Aston, has also recently been constructed in Sydney and whilst only 90m high, has a similar slenderness ratio of 7:1.

Here, an innovative wind resisting system using "offset outriggers" has been developed to reduce building deflections and core bending stresses. This system mitigates some of the disadvantages of conventional outrigger system, such as the outrigger arms obstructing occupiable and valuable floorspace. The offset systems enables the outrigger arms to be placed across the full building width at locations away from the plane of the lift cores.

These outriggers then rely on the floor diaphragms to transfer shear to mobilise the perimeter columns of the building.

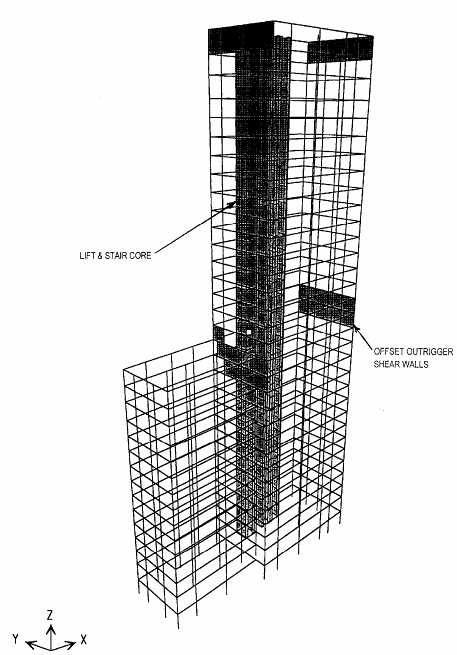

Fig. 4 – Frame Perspective

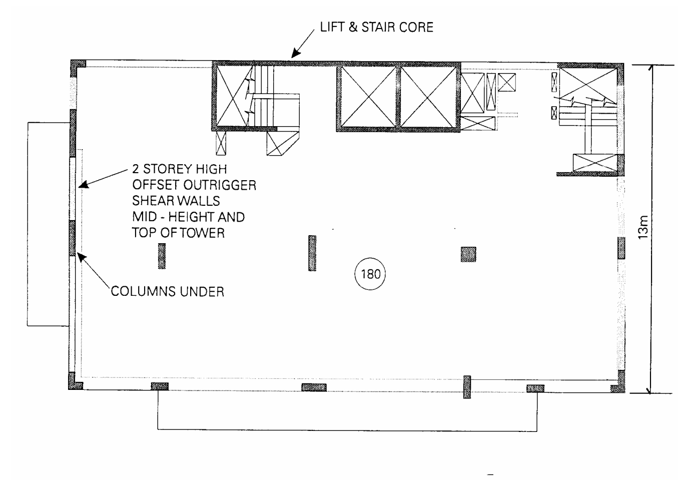

Fig. 5 – Typical High Rise Plan

The offset outriggers, consisting of two storey high shear walls 200mm thick, are located on the side elevations at mid-height on levels 12 to 14 and at the top of the building as shown in Figure 4.

The offset outriggers limit the drift of the building and reduce the bending actions in the core, minimising wall thicknesses and core reinforcement (core wall thicknesses were limited to 200mm even in the lower levels of the building, resulting in a very simple and quick to construct core with no variation of thickness over the entire thirty storeys.

A significant advantage is that the outrigger walls effectively link perimeter columns of similar load and no problems are encountered with differential shortening between core and columns.

The effectiveness of the outriggers has seen the requirement for only a lightly reinforced core, which is required to resist only 20% of the total base bending moment.

WORLD TOWER

The 260m 84-storey high World Tower building has eight below-ground parking levels, nine commercial/retail podium levels with 80 commercial suites, and 665 apartments on 67 levels. It is 28m wide and has a height to base ratio of 9. Construction of the structure was completed in June 2003.

The Structure

The chosen solution includes:

- Central reinforced concrete core boxes coupled by header beams.
- 2 pairs of 8 storey high diamond shaped post-tensioned outrigger walls at mid-height and three-quarter height of the building, which link the lift core to the perimeter columns.
- 2 storey high belt walls located at the tips of each outrigger at the level 37 and 60 plantroom levels, which engage the entire east and west facades to the outrigger walls.
- Outrigger trusses consisting of wind columns and inclined tower columns between levels 14 and 9.
- Perimeter belt beams at the level 37 and 60 plant levels.

Fig. 6 - World Tower South Elevation

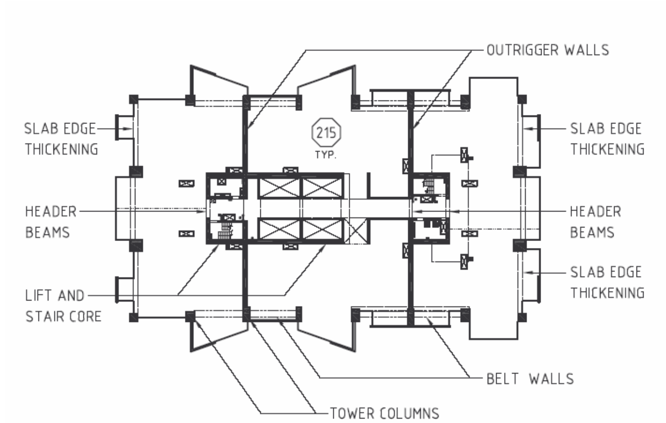

Fig. 7 - Floor plan showing elements of lateral load resisting system

The plan dimensions of the typical floors in the tower are 55m x 28m, with large cantilevered balconies. The typical residential level floors are post-tensioned slabs of flat plate construction spanning nine metres between the core and perimeter columns. The vertical structure of the tower comprises a central core of reinforced concrete, shear wall elements and 20 architecturally expressed columns.

With the lateral load resisting system adopted, approximately 70% of the total overturning moment acting on the building under lateral loads in the critical direction is resisted by a push-pull couple generated by compression and decompression forces in the perimeter tower columns.

Of the 70% of total overturning moment resisted by the perimeter columns, 8% is due to frame action generated by the edge beams, 13% is due to the outrigger truss located at 1/4 height of the building, 30% (the most significant contribution) is due to the lower outrigger walls, and 19% is due to the upper outrigger walls.

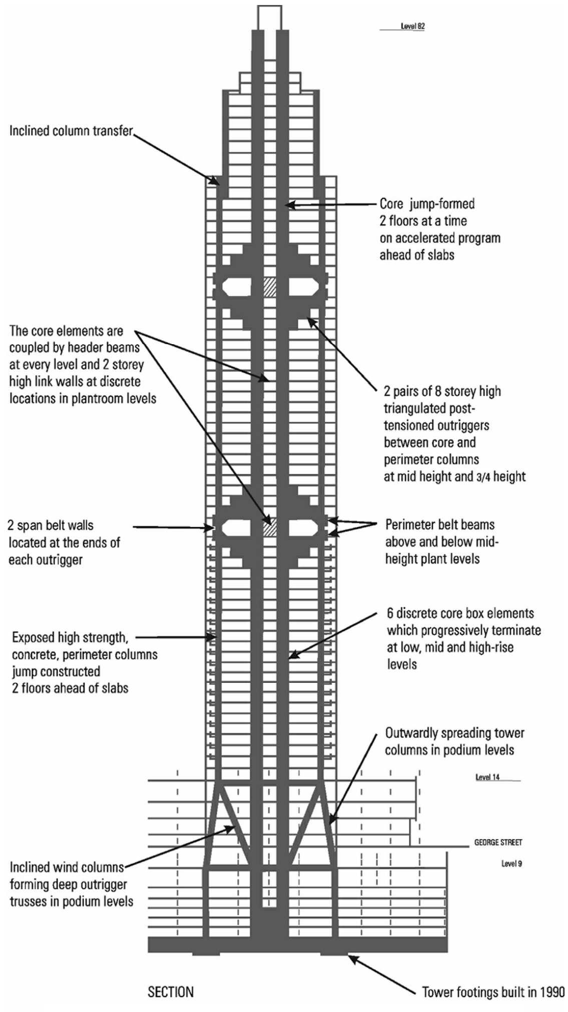

Fig. 8 - Section showing elements of lateral load resisting system

The outrigger system, though highly effective, poses some major design challenges:

- Very large loads have to be transferred across the building between the central core and the perimeter columns whilst minimising disruption to lettable floor space.
- Provision needed to be made for relative shortening between the core and the columns. This shortening was an ongoing effect requiring continual monitoring and management in accordance with the construction program, concrete creep and shrinkage, and building settlement.
- A stiff connection between the core and the columns is essential, with provision made to allow for the relative shortening between the columns.

The chosen solution is a development of the structure successfully used on the Hordern Towers project.

Outrigger Walls

The 400mm thick post-tensioned concrete outrigger walls connect the central lift core to the building's perimeter columns, engaging them as part of the stability system.

The outrigger configuration consists of two eight-storey high diamond-shaped walls hidden within the inter-tenancy walls of the architectural layout. Diamond-shaped walls allowed access along the building at each floor, without compromising the performance of the outrigger walls.

The building stiffness was increased considerably by the development of the outrigger system, and enabled the design team to do away with reliance on supplementary damping systems, which have been necessary on buildings of similar slenderness.

Due to the large wind forces to be resisted, the primary tension reinforcement used in the outrigger walls consists of 50mm and 75mm diameter Macalloy bars shown in Fig 9.

Use of Macalloy bars allowed the bars to be post-tensioned, with the level of post-tensioning adopted in the design to avoid cracking of the concrete under serviceability wind loads.

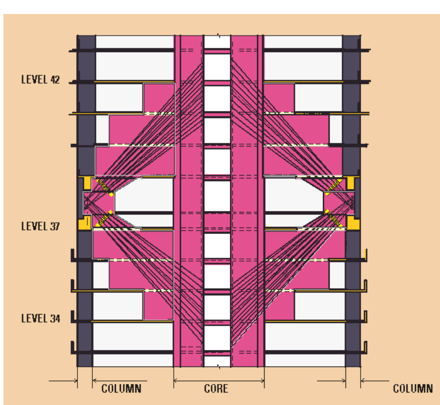

Fig. 9 - Elevation of outrigger wall

Dynamic Response of Tower

Sway in the building's slender direction is caused by westerly wind which is produced by the highest wind speeds in the Sydney region, with a 3 second gust ultimate wind speed of 50 m/s.

The predicted calculated dynamic behaviour of the tower is as follows:

Table 2. Predicted Dynamic Response Parameters

Parameter	Value
Natural frequency (east-west sway)	0.17 Hz
Natural frequency (north-south sway)	0.23 Hz
Damping levels for 5 year wind	1%
Acceleration under 5 year wind (RMS combined)	4.2 milli-g

On site dynamic response testing was carried out by Dr Graham Wood of the University of Sydney in order to confirm critical parameters of natural frequency and damping levels of the building.

The results of the testing is tabulated below. The predicted calculated natural frequencies that were calculated at design stage by modelling the structure using ETABS program are also tabulated below for comparison purposes.

Table 3. Dynamic Response Testing Results

Sway Direction	Calculated Natural Frequency (Hz)	Measured Natural Frequency (Hz) 1st Mode	Measured Frequency (Hz) 2nd Mode	Measured Damping (%) at 0.1 milli-g peak acceleration
East-West	0.17	0.22	0.76	0.77
North-South	0.23	0.32	1.15	0.70

As damping is dependent on amplitude, extrapolation of the measured damping using the Davenport and Hill-Carroll gave a damping level of approximately 1% for 5milli-g acceleration.

For a damping level of 1% the 5 year acceleration prediction of 4.2milli-g is within the recommended criterion of 4.8milli-g for a period of 10 minutes in a return period of five years, proposed by ISO 6897 - 1984.

Outrigger and Belt Wall Connection

In World Tower, to avoid normal perimeter column loads being transferred to the core by the 8 storey deep outrigger walls as the columns shorten more than the core, specially fabricated temporarily adjustable oil-filled flat jacks have been used at the outrigger wall and belt wall interfaces. These jacks are able to transmit the full design forces imposed by the lateral load resisting system, but are adjustable.

Ongoing monitoring of the axial shortening has been carried out during construction and the jacks have been periodically adjusted. Once the building shortening due to creep and shrinkage has fully taken place, the flat jacks will be locked off by replacing the oil with epoxy, requiring no further maintenance.

Monitoring of Axial Shortening

By optimising the level of stress in the core and columns, and ensuring high modulus of elasticity using advanced concrete technology, the differential shortening between the core and columns has been limited to be less than 20mm.

The survey monitoring indicates that the relative movements between the core and perimeter columns appear to have stabilised one year after the end of construction.

Fig. 10 - World Tower, May 2004

High Strength Concrete

The advantages of using high strength concrete of up to 90 MPa (112MPa cube strength) in the tower columns combined with normal strength concrete (typically 40-60 MPa) for the core has had several benefits, including:

- The high strength concrete in the tower columns has a beneficial effect of contributing to the efficiency of the lateral system, both due to increased strength and stiffness resulting from a higher Young's modulus.
- Reducing the differential axial shortening between the core and tower columns.
- Increased net floor area due to reduce column size, as well as reduced obstruction of views which are a prime selling point for high rise towers.

Low Shrinkage, Low Creep Concrete

Use of low shrinkage, low creep concrete also contributed to reduced overall axial shortening of the vertical elements, as well as reduced differential axial shortening between the core and tower columns. The design was based on concrete with a basic drying shrinkage at 56 days as follows:

Table 4. Drying Shrinkage used for Design

Characteristic Concrete Strength f'_c (MPa)	Basic Drying Shrinkage (microstrain)
32 to 50	650
60 to 90	550

Tests of concrete shrinkage for a drying period of 56 days for concrete used in the project are summarised below and indicates reasonable correlation between design and tested values.

Table 5. Drying Shrinkage Measured

Characteristic Concrete Strength f'_c (MPa)	Average Drying Shrinkage (microstrain)
40	630
60	520

EUREKA TOWER

Currently nearing completion, Eureka is a 92-storey apartment building, the tallest in Australasia and one of the tallest in the world. With a height of 300m and a height to width aspect ratio of 7:1, special measures were required to control the tower accelerations under wind.

The adopted floor plan of the low-rise floors is shown in Figure 12 and involves a cruciform shear wall structure which provides the internal vertical support to the floor, as well as acting as a major stability element.

Fig. 11 – Eureka Tower

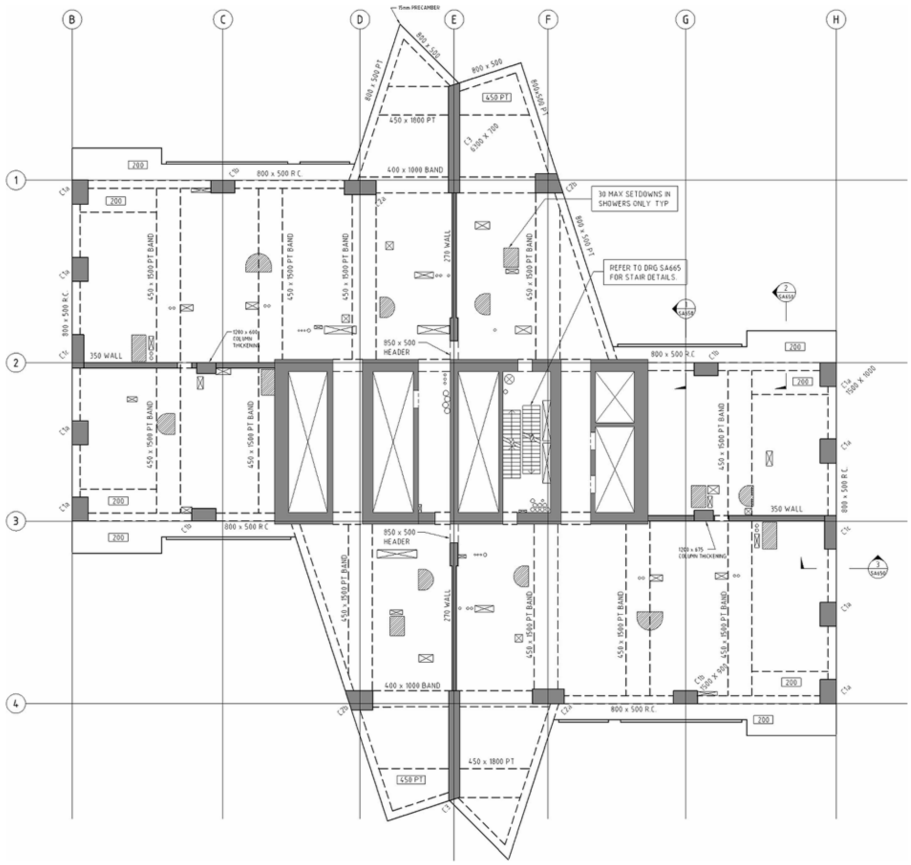

Fig.12 - Eureka Tower

The adopted scheme utilises four of the inter-apartment wall as reinforced concrete outrigger walls, continuous through the residential levels. At the same time, the concept of a mega-column on the north and south elevation evolved, which reflected the architectural concept of a strong vertical element on the elevation.

The main lift / services core is centrally located and linked to the perimeter frame by 300mm thick outrigger shear walls. In order to minimise the core wall thickness, column sizes and to maximise the net useable area, very high strength concrete was used. Strengths up to 80 MPa were specified in the core and 100MPa specified in the columns. Actual strengths achieved on site were up to 125MPa (150 MPa cube strength).

The chosen scheme was developed by integrating the unique architectural design with specific constructability and cost advice and structural requirements, particularly stiffness. From this, and detailed studies of alternatives it was concluded that the cruciform shear wall structure was the most appropriate for Eureka.

It was further concluded that whilst this structure yielded deflection performance which was satisfactory, its acceleration performance was likely to be slightly above the generally accepted limits. Besides the inherent inaccuracies of estimating the building's actual stiffness and natural frequency, the accurate assessment of the building's damping is difficult. This is primarily due to the limited amount of data for actual buildings above 300m tall, particularly with such an unusual shape. Accurately determining the building behaviour was further complicated by the 35m deep piled foundation system which increases the flexibility of the overall structure. The predicted natural frequency of the building is .17Hz and assumed damping to be between 0.8% to 1% at 5 year return period wind loading.

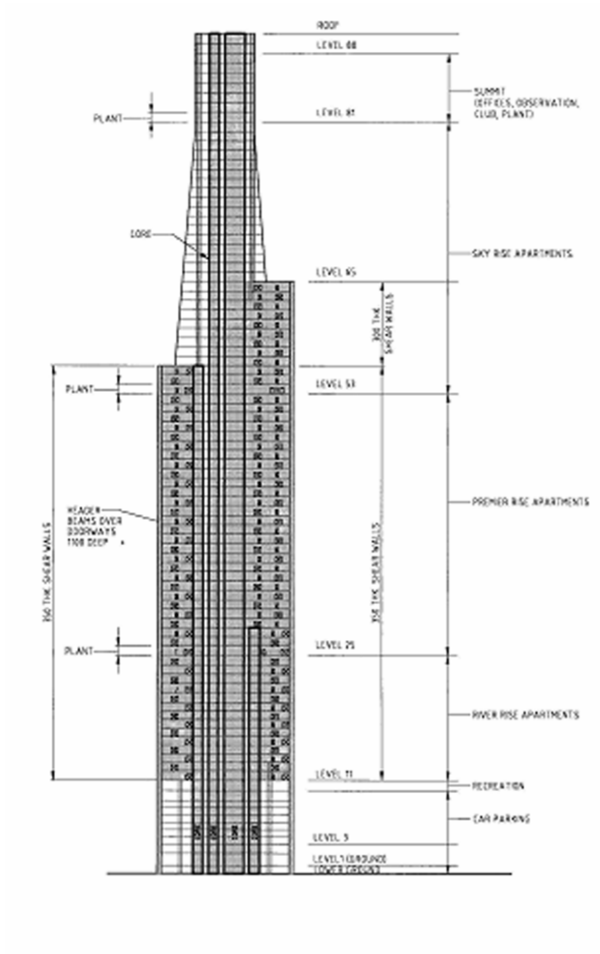

Fig. 13 – Shear Walls - South Elevation

It was finally concluded that the design should make allowance for incorporating additional damping and that full scale tests should be undertaken to confirm the building's structural damping and frequency.

The most common method of increasing a building's damping is to install either a passive or active mass at roof level. This generally takes the form of a tuned mass which weights approximately 2% of the building's mass, located at the top of the building.

For the Eureka Project, a liquid mass damper has been adopted. Compared to a pendulum mass damper, the liquid damper can be accommodated on a single level and can also double up as a rooftop water storage tank as is the case for the Eureka Project.

The role of the tanks is to control building sway accelerations during the more frequent, lower intensity, thunderstorms, the worst of which occur approximately once per year.

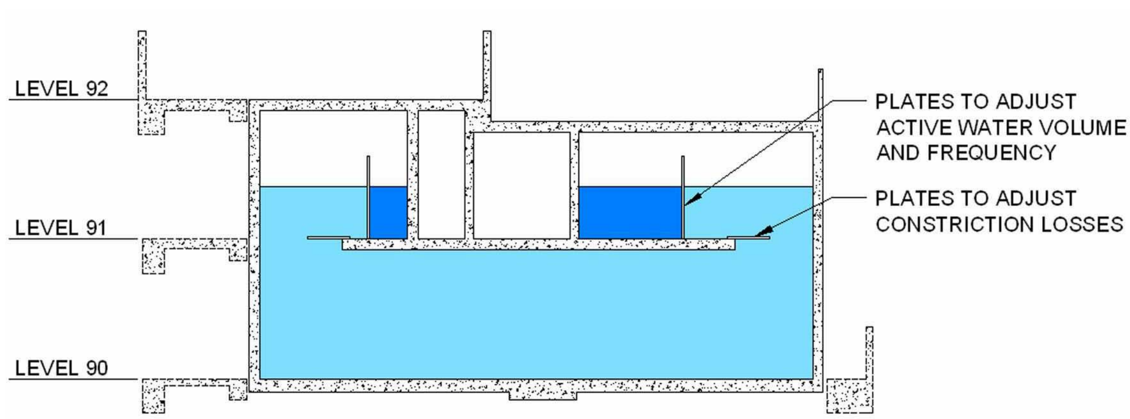

Fig. 14 – Liquid Damper

The addition of the damper tank at the top of the building will more than double the damping available from the concrete core and frame alone. The volume of water required to achieve this level of damping approximately matches that which is needed for emergency fire sprinklers and domestic consumption. We have been able to utilise this water to provide the required additional damping, with a margin of safety to allow for tolerances in the assumed natural frequencies of the building.