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Sky Tower

by
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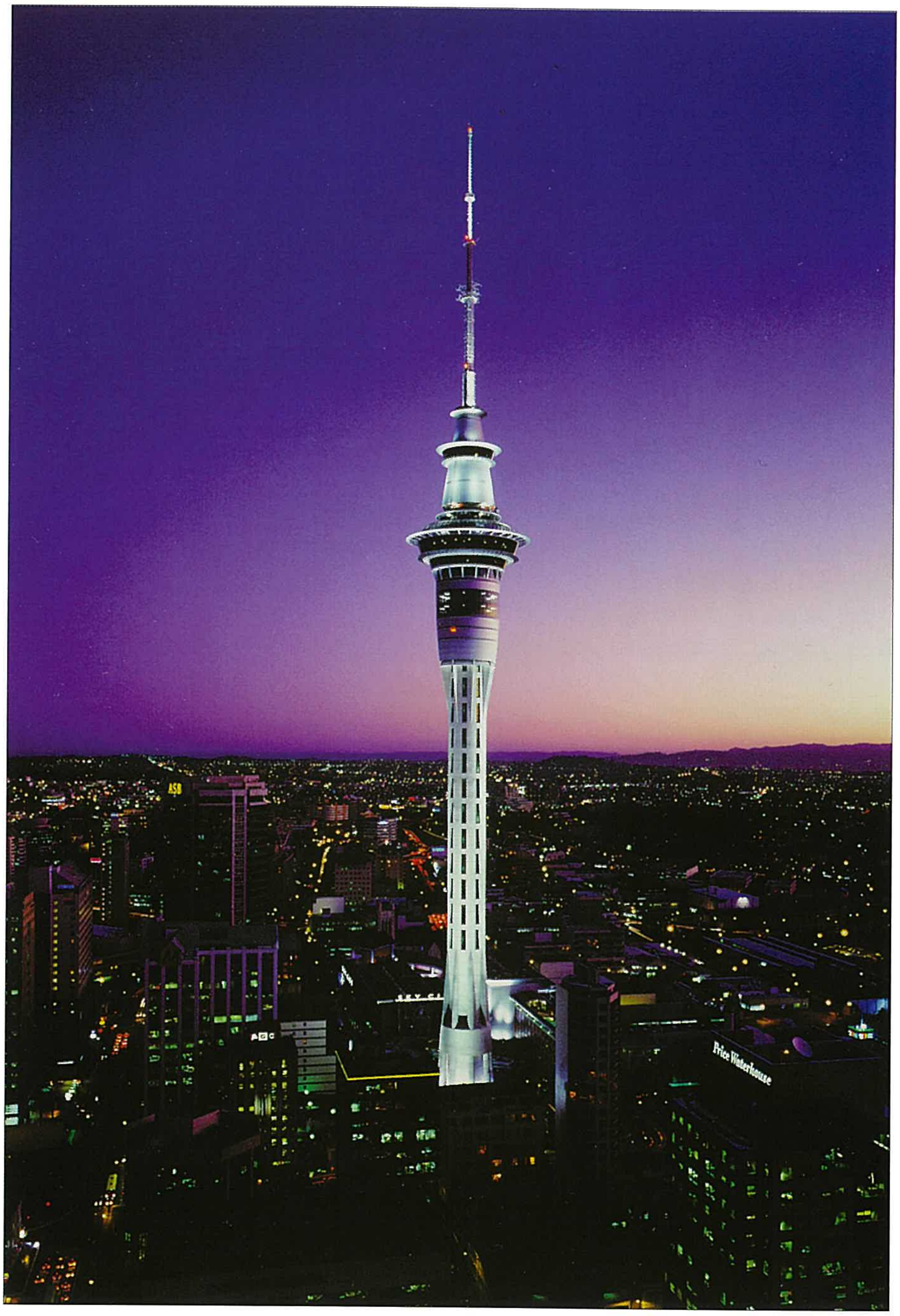
Introduction

Sky Tower is an iconic structure that, since its official opening in July 1997, has come to define Auckland's skyline. Standing 333.6 metres above its foundations and 326 metres above street level, it is the tallest free-standing structure in the Southern Hemisphere.



The Sky Tower.

Beca photo

Characterised by its tall and very slender appearance, Sky Tower has been likened to 'a hypodermic needle' piercing Auckland's skies. While opinions on the structure have varied over the years, the distinctive tower undeniably stands out from the rest of the cityscape and has become a beacon and a brand icon for Auckland and for New Zealand. At night, it makes a stunning statement, when the whole structure is lit up in a variety of colours symbolic of current sporting events, commemorative occasions or charitable causes.

As a commercial undertaking constructed as part of the Sky City casino/entertainment development, Sky Tower draws revenue from tourism as well as from telecommunications and broadcasting operations. It is New Zealand's most visited attraction, welcoming around 500,000 people every year. From each of its three circular observation decks, visitors can get a 360-degree view of Auckland and, on a clear day, one can see up to 82 kilometres in any direction.

A remarkable feat of engineering, Sky Tower's height, long design life and special nature placed it beyond the scope of standard building design codes. The intensive, fast-tracked programme called for a concerted, collaborative effort from the team of client, architect, engineer, contractor and cost consultant. Construction of the foundations for the tower began in September 1994 and it was completed two and a half years later, on budget and three months ahead of programme.

The speed of construction, the owner's requirement for efficiency and the striking concept of the architect presented many engineering challenges that needed to be overcome.

Today, standing proud among the World Federation of Great Towers, Sky Tower is testimony to the ingenuity and skills of its designers and constructors.

Construction Facts

The Sky Tower is made from 15,000 cubic metres of concrete. 2,000 tonnes of reinforcing steel and 660 tonnes of structural steel were used, including 170 tonnes in the mast and 260 panes of glass.

The mast had to be lifted into place using a crane attached to the structure, as it would have been too heavy for a helicopter to lift. To then remove the crane, another crane had to be constructed attached to the upper part of the Sky Tower structure, which dismantled the big crane, and was in turn dismantled into pieces small enough to fit into the elevator.

At one stage there were around 1,000 people working on the construction site. A design team of 140, including engineers, architects, surveyors and others worked on the building at the peak of construction.

The Brief

The client, Sky City Ltd, had a demanding brief. The company wanted to create 'an international quality tourist attraction and an effective, marketable telecommunications facility, within budget and ahead of programme'. Sky Tower had to create a dramatic yet functional landmark for the big-budget

Sky City casino and entertainment development, and the entire project was on a 'hyper-fast track' programme.

As a landmark structure, Sky Tower was designed for an unusually long life of 100 years. This longevity meant it had to be developed with high design standards and durability, as well as low maintenance requirements.

The likelihood of unusually severe events assailing the tower, such as wind, fire and earthquake, is greater than for more standard structures, designed for a shorter lifespan. This meant safety was paramount, and the engineering design team had to incorporate a high standard of Life Safety for both staff and visitors to the tower in their design.

The Structure

The main structural element is the shaft, 12 metres in diameter with a wall thickness varying from 500 millimetres to 350 millimetres. Inside the shaft, a number of internal concrete walls enclose the lift and emergency stairway shafts, and these were cast integrally with the main shaft.

The shaft is supported on eight raked 'legs'. These stiffen the base of the tower and assist in transferring overturning loads to the foundation. A post-tensioned concrete collar transfers the load between the collar and shaft.

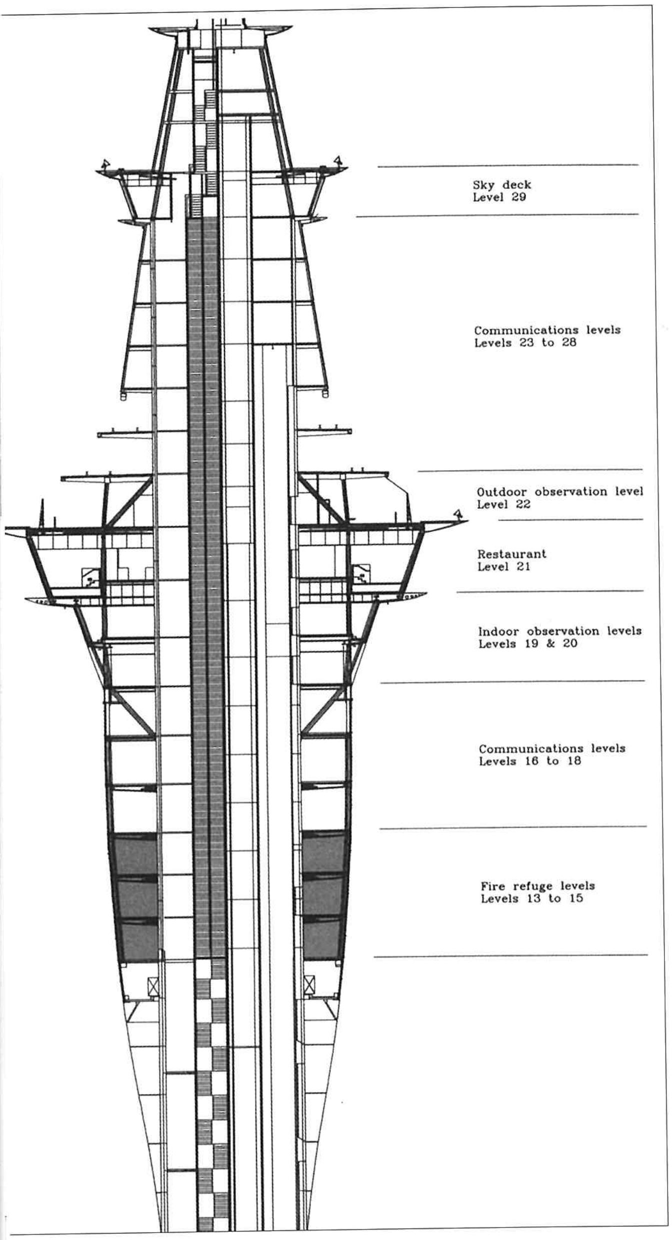
There are three openings in the mid-region of the shaft that allow visitors to see the view from the lifts as they travel inside the shaft. The pod area, on the upper floors of the tower outside the concrete shaft, is constructed using structural steel-reinforced concrete and plain reinforced concrete, with aluminium cladding. A series of hangers and struts were incorporated into the design to avoid using large cantilevers in the mid-pod region.

The concrete shaft ends at a height of 228.6 metres above its foundations. Above this level, a structural steel framework, the pedestal, rises 15 metres to support a concrete ring beam, which in turn supports the steel mast.

Structural Design Elements

Shaft Concrete

The tower is constructed of reinforced, high-performance concrete. A great deal of effort and research went into developing this specially formulated concrete mix to provide a very durable, hard, dense and impermeable material for a long life, with minimal maintenance. It is a tribute to the strong team involved, including the client and the builder, Fletcher Construction, that their focus on getting the concrete mix just right has resulted in Sky Tower maintaining its



Above: Drawing of pod structure.

Beca Group

Top right: The Pod area completed.

David Xu, Beca

'freshly poured' appearance over the years. Its dense surface shrugs off moisture quickly, minimising the build-up of bacteria and organic material.

The mix incorporated silica fume at the rate of eight per cent by volume of cementitious content, with a very high standard of surface finish. The concrete also had to be capable of being pumped to heights of 250 metres and allow adequate placement.

The structural requirements were for a minimum 28-day compressive strength of 45 megapascals (mPa – a maximum of 70 mPa was set to ensure ductile performance was not jeopardised) and a maximum shrinkage of 750 microstrains at 56 days. The testing programme carried out before and during construction confirmed that the specification requirements were successfully achieved.

Foundation Pad

The tower is supported on a 2.5-metre-thick foundation pad, 24.5 metres in diameter, which is laid on siltstone rock. Helping to support the weight of the pad, 16 grooved piles drilled over 12 metres deep are arranged around the perimeter. The tops of the piles are restrained by a ring beam which also confines the rock within the circle of piles. The piles and ring beam are independent of the pad except for a closely-bound reinforcement cage on the centreline of each pile.

The foundation pad was placed in one continuous pour using a standard concrete mix design. The side forms and top of the concrete were insulated with polystyrene to control heat dissipation. Thermocouple sensors placed in various locations within the pad, near the surface and at mid-depth monitored the temperatures for 35 days, and generally the difference in temperature between the core and surface was maintained below the specified maximum of 20°C (the differential was exceeded only at the external corners of the pad).

Construction of the legs and their relationship to the collar.

Gillian Law Beca

The Legs

Precast off site, the reinforced concrete legs were constructed using the same high-quality concrete mix as that of the shaft, using a permanent spun concrete tubular former (a typical pipe section with amended end details). Because these can be seen and touched at street level, it was important to provide a durable and blemish free surface.

To provide a high degree of compression redundancy, the legs are arranged in two concentric cages and are confined with two concentric spirals, one to each cage.

The Collar

The collar is clamped to the shaft using continuous cable loops with in-line stressing anchors, which are stressed from inside the shaft. It would have been easier to anchor the cables on the outside of the collar, but having the anchorage pockets hidden is more aesthetically pleasing.

The capacity of these cables exceeded those readily available, and the anchorage blocks and other features were specially developed for this project. In keeping

Above: Ducts and anchorage boxes from outside the shaft.

Construction Techniques

Below: Fins immediately below the pod cladding.

James Lord, Beca

with the appearance of the rest of the structure, the collar's precast external shell was constructed using the same concrete mix as used in the legs and shaft.

The permanent connection of the legs to the collar had to be left until the collar had been fully constructed and stressed. By this time, the shaft had reached a height of 157 metres. The connection was achieved by extending reinforcement from the legs into ducts in the base of the collar. A 600 tonne-capacity flat jack was placed on the top of each leg and inflated to achieve a 500 tonne preload in the legs. These jacks were interlinked to ensure none could be overloaded if the tower swayed during this operation.

The preload was held for five days to allow some creep to occur. Then, over a calm 12-hour period with little wind, the reinforcing ducts in the collar and the gap between the legs and the collar soffit were pressure-grouted. Finally the jacks were similarly grouted. While the creep will continue, it is expected that long term, under gravity loading, the load in the legs will be similar to that as if they had been constructed integrally with the shaft.

Fins

Eight precast concrete fins radiating from the shaft provide support for the lower pod levels. The fins were individually constructed and attached by stressing through the shaft wall and tying adjacent units together with reinforcement, in post-grouted ducts.

The Pod

Like the rest of the structure, the pod was designed with redundancy in mind. The robust structure was designed so that, even if a column or other critical element was lost, it would still support the design load and the tower would stand.

It is composed of a combination of composite of structural steel and reinforced concrete, and conventional reinforced concrete, with an efficient design that uses a series of hangers and diagonal struts back to the shaft support. Floor slabs act as rings around the shaft, resisting the horizontal strut force.

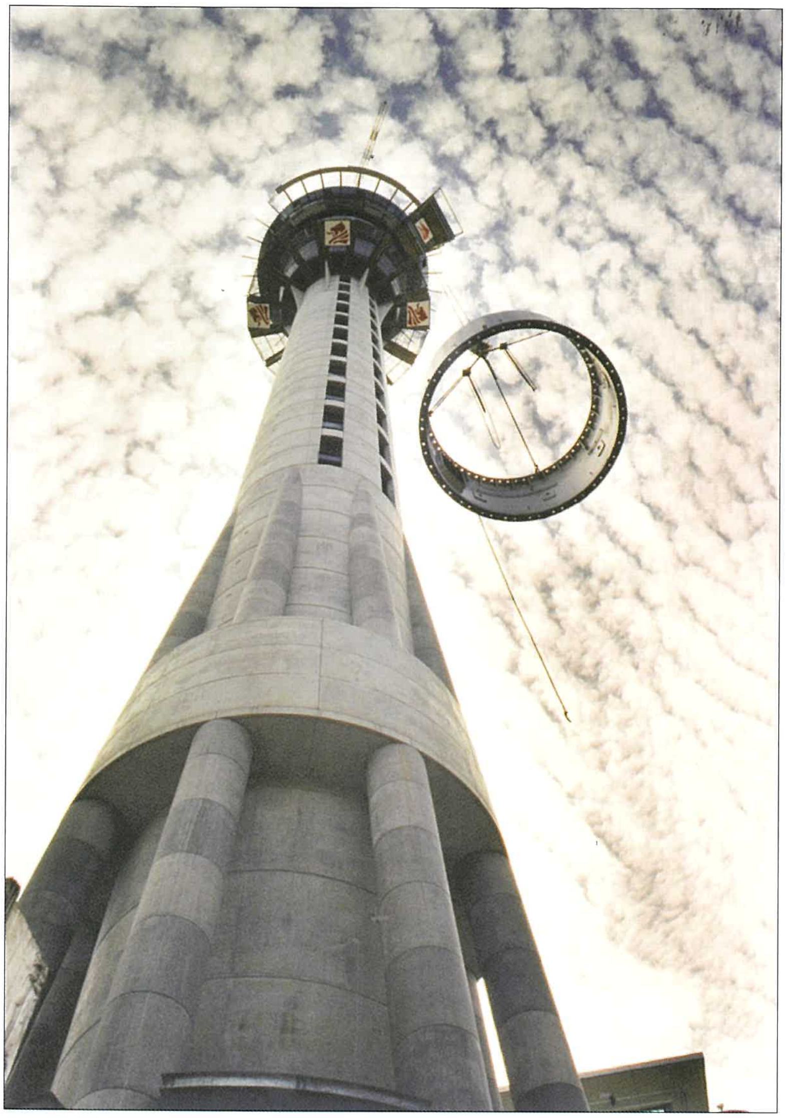
The Mast

Proportioned rather like a giant fly rod, the 92.6 metre communications mast provides space for a host of antennae and other communications equipment, and also acts as a structurally efficient cantilever for the tower.

It is constructed of five steel tubes, ranging in diameter from 4 metres to 0.5 metre. Each tube has several segments bolted together using gusseted flanged connections and a perimeter ring of fully tensioned high strength bolts. The segment lengths were chosen to fit within the lifting capacity of the 7 tonne crane. The tubes have access hatches, cable ducts and access platforms at five levels.

In designing the mast, consideration of fatigue was of particular interest, particularly between the mid-heights of the two upper sections. The design team carried out fatigue analysis in accordance with the procedures set out in the New Zealand standard NZS 3404:1992 [4], assuming a 100-year design life. Guidance on appropriate detailing was also obtained from the British standard BS 5400 [5], and it was also used as an alternative code for verification.

To ensure excellent fatigue performance, a number of measures were implemented, including the use of notch tough ductile steel (a special grade of steel that resists crack propagation in areas of high stress such as corners and notches) and good fatigue-resistant details with smooth weld transitions.



Crane lifting the first mast section into place.

NZ Herald

Seismic Design

Designed to exceed the current New Zealand design codes and standard seismic requirements, Sky Tower 'broke the mould' for seismic design.

Although Auckland is a relatively low seismic hazard area for New Zealand, the tower was designed for a worst case scenario – to remain essentially undamaged in a massive earthquake with a magnitude of 8.0 points on the Richter scale, approximately 20 kilometres away (an earthquake occurring on the inferred extension to the Kerepehi fault, which passes to the east of Auckland City). The tower shaft and foundations have been designed with a dependable (reliable) strength to resist these loads, in recognition of the

Lifting the final mast section into place.

NZ Herald

catastrophic effects a tower collapse would have in the unlikely event of a large earthquake.

A site-specific, probabilistic seismic hazard analysis was used to define the Maximum Credible Earthquake (MCE) for the project, modelling individual seismic sources. This hazard analysis was innovative for New Zealand at the time, as the more common practice was using a uniformly distributed seismicity model. The tower was analysed using both spectral model and time-history techniques.

Finite element analyses were carried out to determine the actions in the shaft coupling beams under lateral loading. To endure non-brittle behaviour of the shaft in circumstances of extreme seismic overload, detailing provisions for ductility have been incorporated.

Wind Design

Auckland City relies heavily on the communications infrastructure on the mast atop Sky Tower. As such, one of the most interesting aspects of the wind design was for the mast (see Liquid Dampers below).

The tower has been designed to remain essentially undamaged when subjected to design wind speeds with a return period of 1,000 years. The entire structure is designed to be able to move as much as a metre in these conditions, and it performs very well in high winds (within 10 per cent of its predicted performance at design). While movement inside the tower can be unsettling for people (for example, swaying of the lift cables), the tower has rarely needed to be shut in high winds due to its excellent performance – and then only for the comfort of visitors.

Statistical investigation of wind data for the design was undertaken by Auckland Uniservices Limited. They compared wind data from three sites in Auckland with the wind speed and return period relationships defined in the New Zealand loadings design code NZD 4203, concluding that it was reasonable to use this code for the non-directional wind speeds for the design of the tower.

The investigators also carried out a series of wind tunnel tests using a model of the site and surrounds to determine wind velocity profiles up the tower and also the cladding design pressures. The code-derived velocity profile was found to be more conservative than these test results and was therefore used for design.

Boundary Layer Wind Tunnel Laboratory (BLWT) in Ontario, Canada, carried out dynamic, computer-based analyses of the tower to establish wind loading response for the tower as a whole. Analyses were performed to determine design forces and actions including the fatigue spectrum for the 100-years minimum life expectation of the steel mast, accelerations in the habitable sections of the tower, the effect of additional damping to the mast and the effects of vortex shedding on both the mast and tower.

Liquid Dampers

While the mast has been designed to meet all performance requirements without the need for additional damping, tuned liquid dampers provide additional insurance against the possibility of increased fatigue stress demands from potentially damaging mast motions. They also provide a higher level of comfort for technicians working inside the mast, as mast accelerations are reduced, improving conditions for installing and servicing antennae.

These liquid dampers have been placed at three positions in the mast: at the top and bottom of the upper section and immediately below the junction between the third and fourth sections of the mast. The dampers consist of donut-shaped tanks filled with a mixture of water, methanol, a biocide and an anti-corrosion agent.

The tank levels have been 'tuned' to match the frequencies of the first two mast modes involving significant mast response, and are the second and third modes of vibration for the tower as a whole. All structures have numerous modes of vibration, e.g. first mode for the tower is the oscillation where the top of the tower swings back and forth and second mode is where the tower is stationary at the top but the tower oscillated back and forth near its middle (approximately). The majority of the mass and 'action' for Sky Tower's mast participates in the first three modes. Therefore, we put 'tuned mass dampers' in positions to best dampen the excitation from these modes.

As the mast moves, energy is dissipated from the form drag, due to the sharp edged baffles that intercept the sloshing fluid. The effect is to raise the damping in the steel mast modes from about 0.3 per cent to in excess of 1 per cent. As the size of the dampers in the upper section of the mast is restricted, the extent to which the damping could be increased is limited. However, the level of damping achieved is expected to greatly improve the in-service performance of the mast and its attachments.

Fire Engineering

Sky Tower posed a brand-new fire engineering design challenge. Its sheer height means that a mass evacuation of occupants to the ground level is impractical. With 1,267 steps from the base of the tower to the viewing deck, it would pose a very challenging physical ordeal even for fire service personnel, and severely hinder their ability to effectively fight the fire once they got there.

As New Zealand's first and highest tower, research into other unique towers, such as the CNN and Eiffel towers, and close collaboration with the contractor to find the safest and most effective options was invaluable. The design was reviewed by a world renowned structural specialist.

The solutions included incorporating an intrinsically safe 'fire refuge' within the pod section, including a command centre that provides four hours of protection. Both passive and active fire protection features have been maximised to ensure there would be enough time for safe egress to the fire refuge, and a dedicated and well protected fire service lift has been included for staged evacuation.

Electrical Services and Lighting Protection

As a commercial venture that had to be marketed as a sophisticated broadcast and communications centre, Sky Tower needed high quality building services infrastructure with a host of special features within the electrical services systems. Not the least of these was a power supply system that minimises the practicable frequency and duration of operational outages. A high degree of redundancy was also built into the electrical distribution system.

A state-of-the-art lightning protection system and coordinated surge protection systems help to minimise the risk of lightning or other transient induced damage of critical electronic equipment. Multiple earthing systems provide for life safety and also avoid electromagnetic interference to the broadcasting and communications equipment.

The lighting included an aviation warning lighting system developed in conjunction with the Civil Aviation Authority, and it took a great deal of illumination engineering expertise to find an effective means of flood-lighting this tall spire rising into the night sky. The initial spectacular lighting design, while since replaced by more modern LED systems, inspired a fascination with Sky Tower's appearance by night that still endures today.

The design of all these systems required substantial research into the latest available technology at the time as well as an unprecedented level of design detailing to meet the performance objectives.

Conclusion

Sky Tower's success story as a landmark project can be attributed to the close collaboration of the architect, contractor, client, cost consultant and engineer throughout the project, focused on a shared vision of excellence. The tower's careful balance of function and form has created a legacy that will continue to be enjoyed by future generations of Aucklanders and the visitors who will marvel at the scenes from its viewing decks high above the city.

When a thing is done well, it is often emulated. The Macau Tower in the People's Republic of China is based on Sky Tower, paying tribute to its outstanding architectural and structural achievement.

However, for the Auckland communities who see its familiar outline every day, Sky Tower is simply a beacon that says, 'I'm home'.

Project Team

Owner: Sky City Ltd
Contractor: Fletcher Construction Ltd
Cost Consultants: Rider Hunt Holmes Cook Auckland Ltd
Architect: Craig, Craig, Moller Architects
Engineer: Beca, Carter, Hollings & Ferner Ltd

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