Title: **The Construction of a High-Rise Development Using Volumetric Modular Methodology**

Author: Phillip Gardiner, Managing Director, Irwinconsult

Subjects: Architectural/Design
Building Case Study
Construction
Economics/Financial

Keywords: Design Process
Economics
Modular Construction
Sustainability

Publication Date: 2015

Original Publication: The Future of Tall: A Selection of Written Works on Current Skyscraper Innovations

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

The Construction of a High-Rise Development Using Volumetric Modular Methodology

Phillip Gardiner, Managing Director, *Irwinconsult*

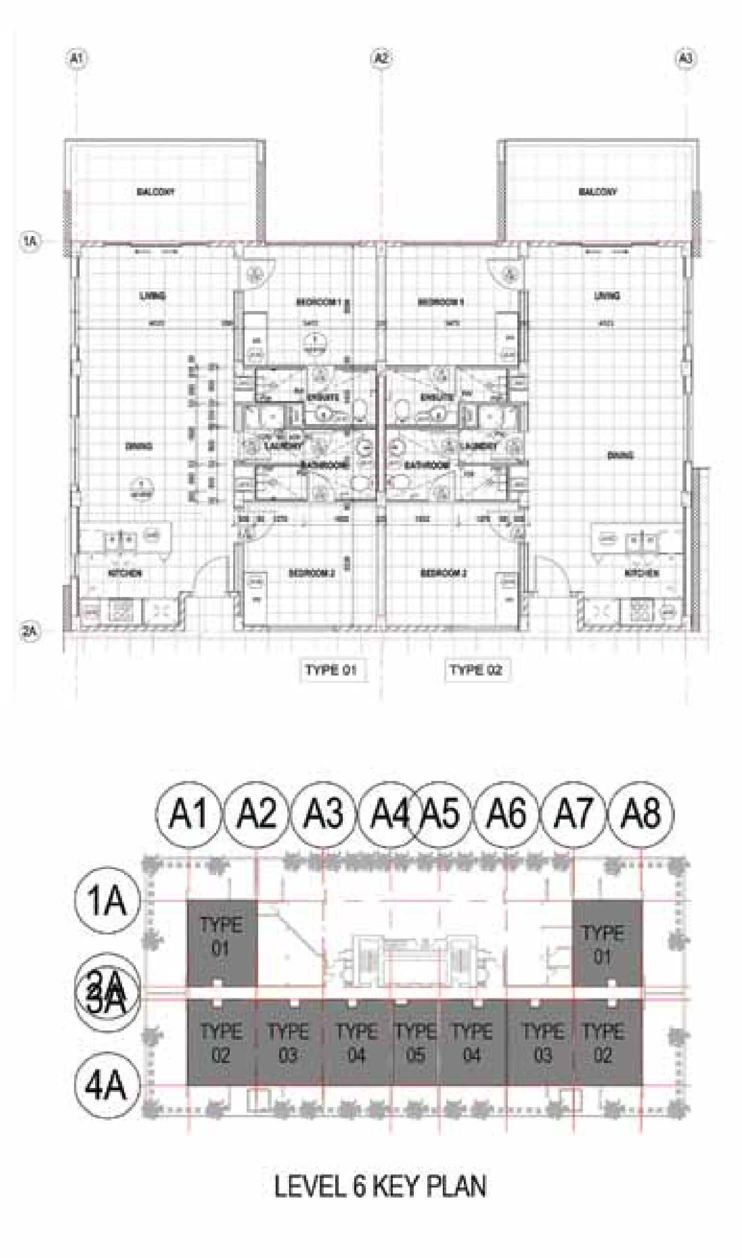
The SOHO Tower is a 29-level modular building in Darwin, in the far north of Australia, a cyclonic region. The building was designed to incorporate a basement and eight floors built with conventional reinforced concrete followed by 21 levels of volumetric modular apartments. The modules were constructed and fully finished in Ningbo, China and shipped to Darwin. Unlike most modular systems, a concrete floor was used with concrete columns poured on-site into formworks contained within the modules. The building's lateral stability system came from the central core using a modular precast concrete system, above level 7. The choice to "go modular" was driven by a constrained and high-cost labour market. The concrete floors were initially a client request, but proved to have other advantages. The concrete columns satisfied the loads generated by 21 levels of concrete-floored modules.

Why Modular?

At the time of commencing design in 2011 and construction in 2012, Darwin was in the midst of a boom in construction and a significant shortage of accommodation. This was predominantly driven by the development of a large gas processing plant employing many thousands of workers, including construction workers, but also a large number of "fly-in-fly-out" specialists residing in hotels and apartments across the city.

The SOHO tower had been initially designed, received planning approval and its' apartments substantially presold based on conventional construction, nevertheless the cost and shortage of a skilled construction workforce led to a decision to investigate a volumetric modular alternative, with modules delivered complete with all finishes, joinery and fittings. It was essential however that the building layout and appearance not be changed in any substantial way. This was a significant challenge.

Another driver was the foundation conditions. Darwin is underlain predominantly by a crust of soft Porcellanite rock overlying softer Cretaceous sedimentary deposits of Phyllite to a very significant depth. Buildings have been typically founded on pads or rafts founded in the soft rocks at bearing pressures that would not cause unacceptable levels of settlement. The



Right: Architectural apartment floor plans. Source: Irwinconsult

Opposite: Construction image of SOHO. Source: Irwinconsult

allowable peak bearing pressure on this site is 500 KPa, a challenge for a 30-story building that would typically require a full raft across and beyond the tower footprint. Lighter construction methodologies, such as modular, were also considered to be an advantage for this circumstance.

Critical Design Parameters

The geotechnical conditions have been summarized in the previous section. There was an absolute limit possible on building mass and this had already driven the reconfiguration of car parking to omit a basement. The original scheme proposed two basements, which resulted in insufficient residual "rock" thickness above the softer sedimentary materials to spread loads and control both absolute and differential settlements. This controlled the maximum possible weight of the structural system and applied finishes.

The severe cyclonic conditions in Darwin result in very high wind loads. The average applied wind pressures to the building were determined by wind tunnel testing to be 7 KPa (unfactored) with peak local pressures on façades in excess of 13 KPa. This precluded the use of self-braced modules. A "traditional" core with an outrigger wall was found to be the best structural solution to control wind induced deflections. The critical stresses on the core walls were tension forces, as with most residential buildings, with a partially external core and fewer lifts for a given floor area than a commercial occupation.

Given that contracts of sale were in place for the apartments, the developer, who was also the building contractor, ultimately had a preference for a concrete floor and a building that, when completed, matched as closely as possible one of conventional construction. There was also a planning limit on total building height of 90 meters. This fixed story heights at 3 meters.

The other critical criterion was the design for shipping and handling. The lifting system relied on a vertical lift from the eight perimeter columns. Spreader beams were designed and fabricated to satisfy this requirement in the factory, on the wharf and on-site with appropriate dynamic factors of 200% as prescribed in the *ABS Rules for Certification of Containers 1998*.

Transport on a 2.4-meter-wide truck without any special frames controlled much of the floor design, particularly to avoid excessive deformations under dynamic loads.

Stacking of modules up to four high at the factory and storage yards also had to be considered, as did two-high stacking onboard a ship. The requirements for ship transport, including temporary lashings, were also designed to comply with the *ABS Standard*.

The modules were designed to comply with the Australian Building Codes and Standards. Where Chinese materials (steel, reinforcement, and concrete as well as plumbing and other components) were used, test certificates and reports from NATA registered testing laboratories were provided.

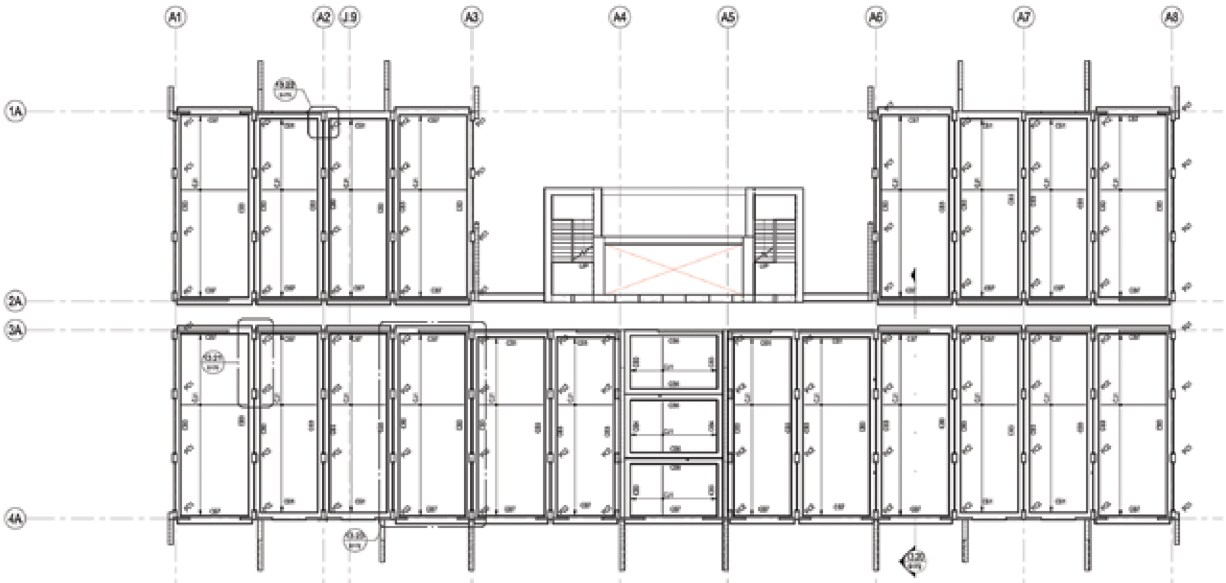
Modular Design Options

The first design solutions presented for consideration were steel framed in line with what had been seen in local Australian markets and on a research trip to China. Systems that would deliver 21 levels were not encountered, however, and even less so given that they had to conform to a predetermined layout and resist cyclonic wind loads. Sketch designs for a steel framed solution with tubular steel columns and a steel framed floor with "autoclaved aerated" floor panels were developed. A prototype was built in the developer/contractors' precast concrete factory, although it was already planned to construct the modules in China.

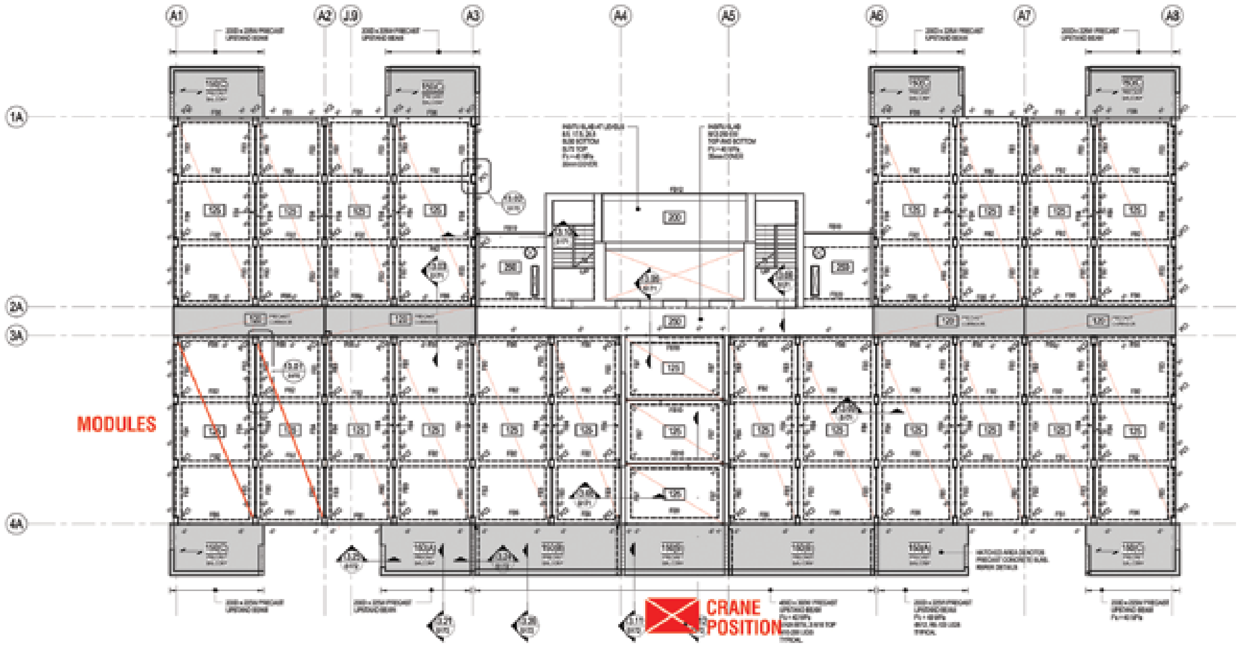
Details were developed to achieve the necessary fire ratings and acoustic separation. The relevant Australian Standards required a 90-minute resistance for structural elements and 60 minutes for non-structural fire walls in a building of this size fully equipped with sprinklers.

Difficulties envisaged with the steel solution were:

- Each apartment comprised two modules measuring 10 meters x 4.2 meters and 3.9 meters respectively. For a fully steel framed option, the wall between the two modules would need a 90-minute fire rating to protect the steel structure and to prevent the spread of fire between floors. While achievable, it added complexity and additional fire ratings to ceilings and walls.



STRUCTURAL CEILING PLAN



STRUCTURAL FLOOR PLAN

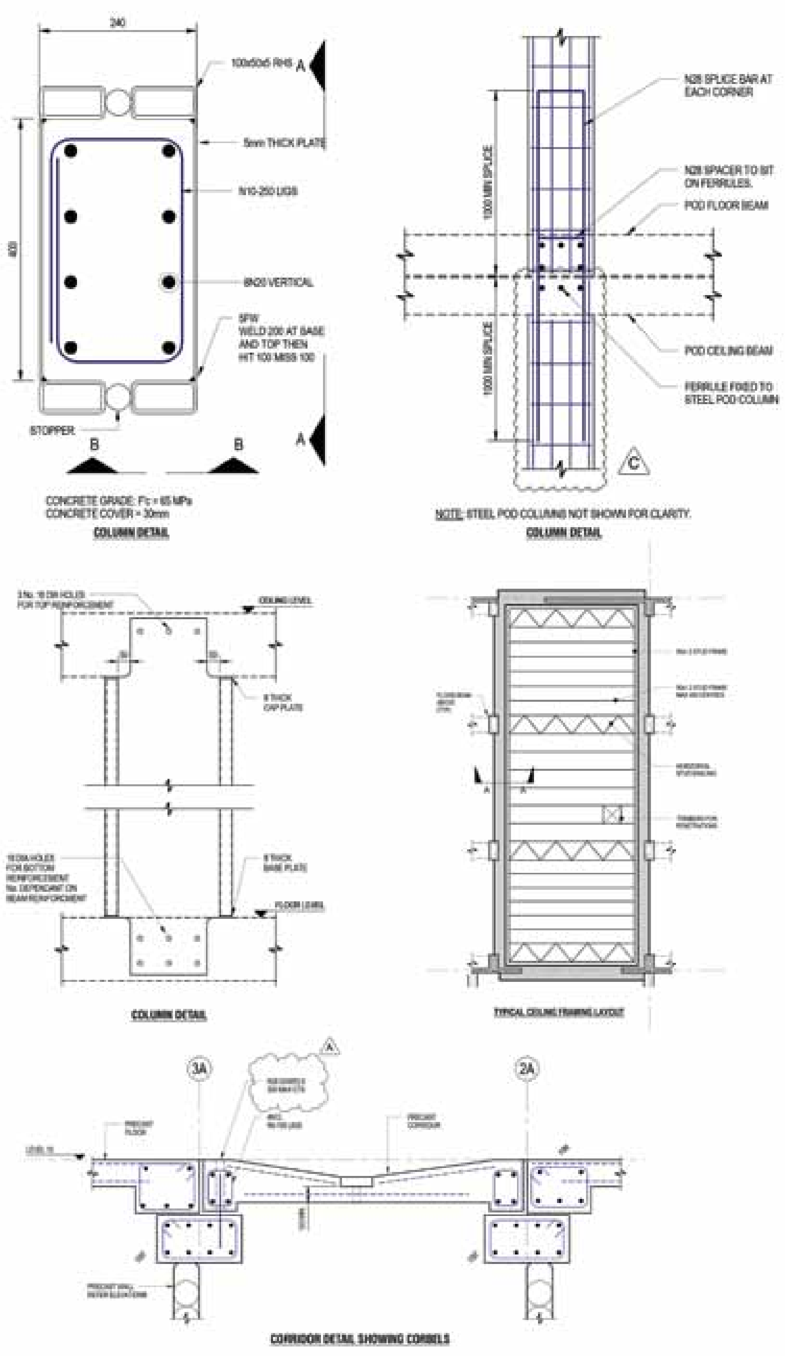
- The limit on floor-to-floor height and a less than ideal location of plumbing risers made it difficult to connect sewers from showers and other fixtures under the floor without penetrating multiple steel joists or compromising ceiling heights.
- The width of the modules would have made it necessary to transport them on spreader beams on trucks both in China and Australia after shipping.
- Darwin has a very tropical humid climate and there were real concerns with controlling condensation on cool exposed steelwork in interstitial spaces between the modules.
- The number of elements and time to fabricate modules was considered excessive. Particularly given that a new manufacturing facility was to be established by the developer in Ningbo with a Chinese, but Australian-owned partner. There would not be time to set up the production lines needed to achieve program and quality.

Following this experiment, a "concrete" solution was developed, the significant limitation of this being the weight for both building loads and foundation constraints, as well as handling and transport from the factory to the site. An initial target maximum of 22 tons per module was set based on the anticipated capacity of the site crane at its maximum reach for the placement of the modules.

The concrete floor was designed as a slab with perimeter beams and cross beams located to intersect with the perimeter columns. The cross beams assisted to reduce the slab thickness as well as ensure columns were well connected to the floor. They also allowed a 4.2-meter-wide module to sit on a 2.4-meter-wide standard truck bed without the need for a spreader frame. Truck transport of the modules was determined to be the critical load case for the slabs, after an allowance for a 170% dynamic impact factor was considered along with the serviceability limitations necessary to prevent cracking of the plasterboard, glazing, tiles and joinery incorporated into the completed modules.

Opposite: A typical structural layout for apartment and hotel module floors and ceilings. Source: Irwinconsult

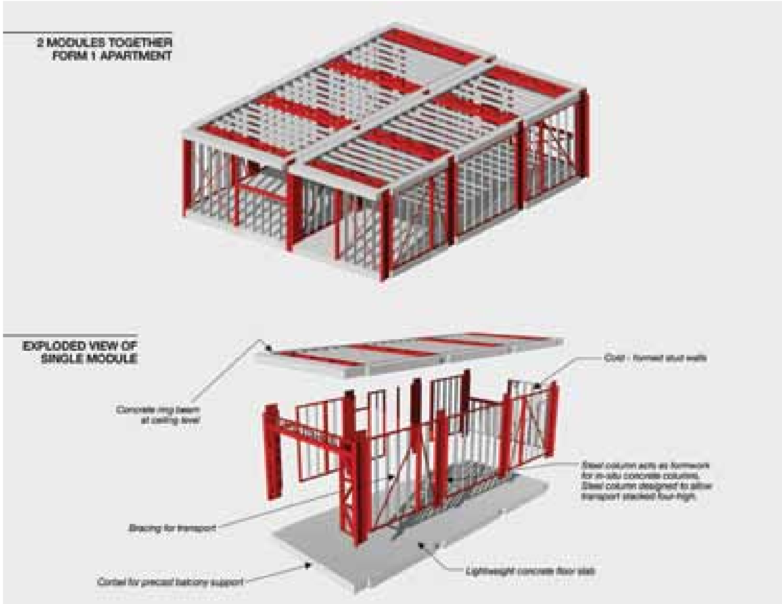
Right: Column and corbel details. Source: Irwinconsult



The 125-millimeter slab and beams (300 millimeters wide x 250 millimeters deep) are of smaller proportions to most conventional concrete structures and required some control of detailing and placement of reinforcement. Various configurations of tensile and shear reinforcement were trialed to ensure easy placement and quality. Beams were also positioned so that no sewer pipes had to cross them. The slabs incorporated concrete corbels at the front and rear to support the corridor slabs and balconies that were constructed predominantly with precast concrete elements added after the erection of the modules. The floor slabs were poured upside down on steel forms at the factory. This ensured the consistent set out of wet areas and accurate grades to wastes.

The slabs also contained cast in steel fitments for the attachment of wall framing and mullions for glazing. The reinforcement for the cross beams had threaded ends which allowed the attachment of steel column forms via "elephant foot" ferrules which also served to anchor the reinforcement to the columns.

"The SOHO tower had been initially designed, received planning approval and its' apartments substantially presold based on conventional construction, nevertheless the cost and shortage of a skilled construction workforce led to a decision to investigate a volumetric modular alternative, with modules delivered complete with all finishes, joinery and fittings. It was essential however that the building layout and appearance not be changed in any substantial way. This was a significant challenge."



Top: Exploded view of the module structure. Source: Irwinconsult

Bottom: Lifting a module from storage. Source: Irwinconsult

Opposite: Final positioning of a module. Source: Irwinconsult

In order to provide a concrete floor while achieving reasonable weight limits, a lightweight concrete mix was specified using an expanded shale aggregate. A density of 1,600 kg/m^3 was proposed and was to be controlled through the monitoring of densities at the factory.

A batching plant had been set up there to ensure a continuous supply of concrete and strict control over strength and density. Testing of trial pours showed that the specified strength could not be consistently achieved at densities less than 1,800 kg/m^3 and the designs were adjusted to suit the extra load.

Hot rolled mullions, sills and heads were used to trim the glazing and doors in the end walls to provide some sway stiffness for transport. Cold formed steel studwork was used for other walls with heavy gauge studs used for external walls to allow for the stacking of modules in the factory and on a ship, and to resist the internal wind pressures that could occur if glazing was breached during a storm event.

The design for the modules' ceiling framing needed to ensure rigidity, water tightness during transport and adequate fire and acoustic separation. This led to a partial concrete solution. A concrete ring beam was incorporated into the perimeter of the ceiling. This ensured that all column load paths were transferred through concrete elements with a fire rating of 90 minutes. Therefore all walls became non-structural in the permanent case, allowing intertenancy walls and the ceiling to have a 60-minute fire rating, satisfied by one sheet of 16-millimeter fire rated plasterboard on steel studs and joists. The internal walls required no fire rating.

The concrete ring beam also corbelled to support other elements and provided rigidity at ceiling level for the lifting and stacking of modules. The lightweight ceiling within the ring beam was constructed from

cold formed steel joists with a fire rated plasterboard lining. A waterproof metal cladding was applied to the outside of module walls to provide weather protection during transport and erection.

All steel frames were further protected with a polyurethane foam insulation applied by spraying at the factory. This improved acoustic and thermal insulation and acted to eliminate condensation issues.

Handling, Transport and Shipping

A weight of 22 tons was targeted to meet the anticipated limitations of the site crane. The change to a heavier concrete mix and the addition of bulkheads and other finishes, pushed the total weight to 26 tons. This was not an issue for handling at the factory or for truck and ship transport, but proved to be right on the safe working limit of the 65-ton tower cranes already in place on the site. A redesign of lifting gear from heavy chains to lighter slings reduced the total load to be within safe limits.

Ultimately, the modules were positioned with minor or no defects arising from their transport from the factory to their final position on site. The minor defects in finishes and treatments were only apparent in modules shipped during a typhoon and were therefore subject to more extreme loads.

Ferrules and other attachment points were built into the modules to facilitate lifting and lashing with standard equipment. They were also fully shrink wrapped in plastic before leaving the factory to provide an added layer of protection during transport.

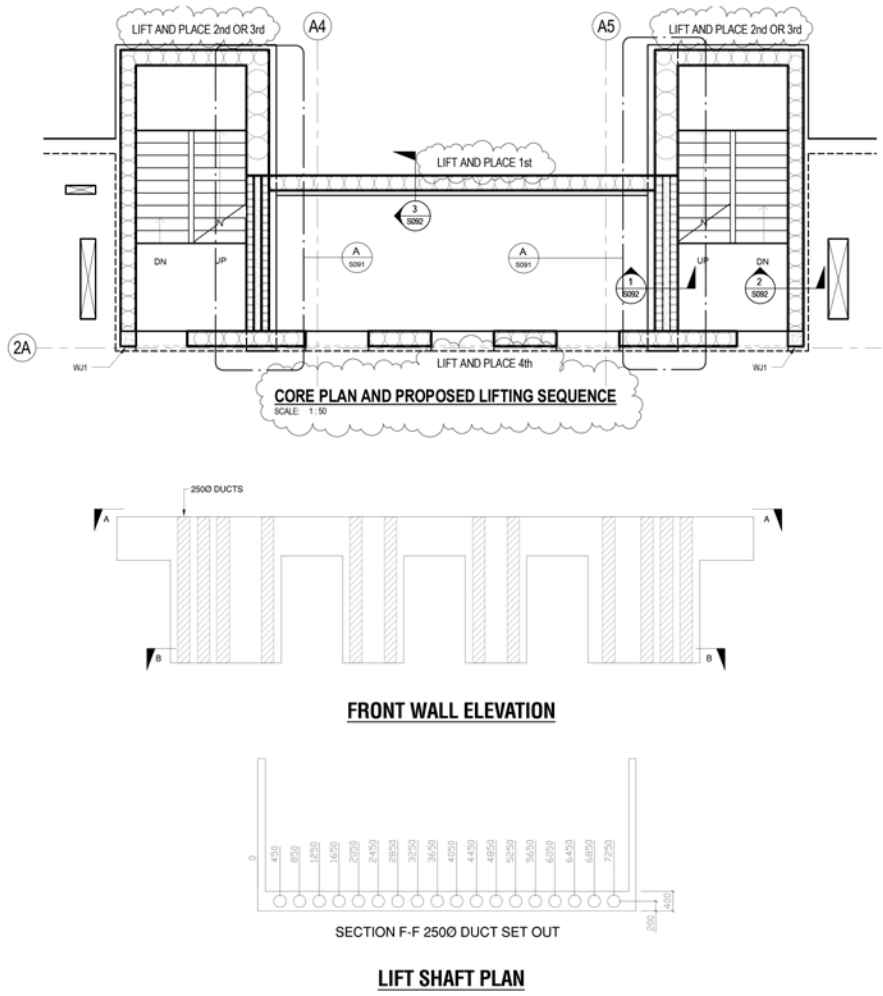
Tolerances and Positioning

The modules were manufactured to a tolerance of +/- 10 mm. For a "stacked" module system over 21 levels cumulative tolerances would have been an issue, however given that the columns supporting the modules are constructed in situ, the positioning can be adjusted on a floor-by-floor basis. Prior to the erection of each floor, the tops of the modules on previous floors were surveyed and Teflon shims provided under bearing points to ensure that each module on the next floor was aligned and level. Positioning of individual modules was achieved by conventional site construction techniques, i.e., manpower on the end of crowbars and with rope guides. This is something that can be improved on future projects if some self-guiding fixtures can be incorporated into the design.

Stability Systems

As mentioned previously, the tower is subject to very high wind loads during a cyclonic event. Lateral stability is provided by connecting modules to the core on a floor-by-floor basis. This is achieved by utilizing the corridor slabs which connect to the modules and core as diaphragms and by connecting directly to the outrigger walls running centrally from the core. Overall building stability is given by the core and outrigger wall structures. Traditionally these would have been constructed in Australia using a jump-form or similar system, with the core progressing ahead of the floors.

To give flexibility to the program and make module erection easier, the erection of the core could proceed somewhat independently and behind the modular floors by up to four levels. The proximity of the large tower crane close to the core and the amount of free crane time suggested that a precast core could be a solution.



Left: Core details and lifting sequence. Source: Irwinconsult

Opposite: Soho Apartments completed. Source: Irwinconsult

The normal disadvantage of a highly stressed core constructed from flat precast panels is the difficulty in connecting corners and junctions to transfer high shear and tensile forces.

The high crane elevator capacity at the core location (38 tons) made it possible to consider using three-dimensional boxes for the core. We rationalized this to four elements being the two stair shafts, the three elevator shafts and a front door panel.

The precast elements are proportioned and configured to virtually eliminate mechanical connections and formwork for "wet-joints." The three-dimensional nature also eliminated the need for any temporary propping. In-situ concrete is poured between the panels of the stair and elevator shafts and there is a small formed and poured section over the heads of the stair doors to provide continuity from the door panel to the stair shaft.

Connecting precast elements at each floor level to transfer high compression and very high tensile forces was the other issue to resolve. The initial concept utilized proprietary bar couplers. These were effective, but time consuming to install and created significant congestion. After constructing several floors using this technique the issue was revisited and the team decided to cast vertical circular "column" voids into the precast components. These ranged from 150 millimeters to 250 millimeters in diameter. The results showed they could contain all tensile reinforcements and that the compressive forces could be transmitted solely through these "columns."

The consequential benefits were lighter panels with simple vertical reinforcement and conventional cages and laps for "column bars." This significantly reduced cost and increased construction speed. Similarly, the outrigger walls comprised a combination of in-situ and precast elements connected to the modules at floor/ceiling interfaces.

Balconies

It would have been desirable to incorporate the balconies into the modules, but given the layout that was locked in and the already high unit weights, it was necessary to construct the balconies independently. These were also designed as precast concrete units supported by dividing precast walls and attached to the modules for stability and serviceability purposes only.

Balcony floors were tiled in the factory and had the option to pre-fit balustrades before erection. They were brought to site with dividing precast walls as "U" shaped units and lifted into position. These were again designed to be able to be erected on an independent program to the modules allowing maximum efficiency of site labor and cranage.

Lessons Learned

Despite commencing with very little time to build and test prototypes, the construction came together as anticipated in the design. However, there are some issues that could be improved:

- Reinforcement congestion in small beams and columns was delaying manufacture and construction early on, but detail adjustments resolved the issue for the beams. The Placement of reinforcement into the columns between modules was still a tedious issue and further research has been done to resolve this for future projects.

- A major issue was the ingress of water into finished modules during Darwin's tropical storms. At critical times during erection, the shrink wrap skin was removed and the columns prepared for concreting. Rain at that time could fill the column voids and water inevitably would find a way into the modules, staining finishes and requiring remediation. Better waterproofing systems have been developed for subsequent projects.
- The placement of modules into an exact position was labor intensive and took longer than expected. The incorporation of details that guide modules into position will improve this.
- Riser shafts for plumbing were located in bathrooms, meaning that final fitting connections had to be done from inside apartments, which had been delivered complete with all finishes, joinery and sanitary ware. Positioning risers adjacent to corridors and balconies would be preferable. The less work required inside modules on site, the less clean up and repair of accidental damage required.
- Keeping module weights less that 20 tons would be an advantage as this is the capacity of many cranes, trucks, etc. Designs have been progressed achieve this while still maintaining the benefits of concrete in the modular structures.
- The continual control of quality and work methods at off-shore manufacturing facilities is essential. This was resolved by having representatives of the contractor's key trades at the factory for much of the process. This also allowed for training of factory staff in the construction methodologies required.

In Summary

The designs developed have delivered what is currently thought to be the world's tallest volumetric modular building. This was done in a remote city with a constrained labor force and challenging climatic and geotechnical conditions.

Unlike most modular systems, the design and construction aimed to replicate conventional construction techniques at a low level of sophistication. The advantage of this was that the factory was able to operate as a "construction site in a shed," with no major investments in plant and equipment and with a relatively unskilled workforce.

Erection on-site was also able to be completed with a casual, unskilled workforce on short term visas. The system is also capable of being used on much taller buildings provided that columns can be accommodated in the planning and that a core is provided for stability systems.

The disadvantages of the system are the weight of the modules relative to steel framed systems and a slower construction program, although this system should achieve program savings of 30% over conventional construction. This could be improved further with the incorporation of more principles of Advanced Manufacture for Assembly.

The lessons learned have resulted in improved detailing for a future 50-story development now in the concept stage.