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Frame apartments - case study in modern concrete high-rise construction in New Zealand

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ABSTRACT

Frame Apartments is one of Wellingtons tallest residential buildings and a testament to how unique function, design, and innovation can be combined to create an enduring property that works within its environment while further enhancing the urban fabric of the city.

The constraints of the site required a slender yet rigid structure to house the planned 54 apartments. In addition to Wellingtons significant seismic demands, wind sensitivity was highlighted as a critical design challenge requiring a blend of pragmatic and innovative solutions. The final design incorporated an extruded exterior shear wall system which achieved both a unique aesthetic as well as a structurally efficient and economic construction.

Further material efficiencies and architectural expression were gained in combining the use of the concrete superstructure with the interior and exterior finishes. The clever use of warm construction utilised the inherent thermal performance of the concrete walls, leading to a sustainable, efficient and practical solution.

The new building has already gained considerable attention for its unique character and construction approach. The exterior walls were notably constructed using an innovative climbing jump-formwork system, which allowed the Contractor to cast in-situ multiple stories between craning in the rib-and infill precast floor system and internal gravity framing. This provided significant benefits in regards to construction efficiency and quality control, as well as, environmentally with significantly less waste requiring disposal.

Frame Apartments is set to become a distinct and enduring Wellington landmark where the extensive use of modern concrete design and construction is fully celebrated.

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1 INTRODUCTION

In 2015 Aurecon was appointed by developer Vicinity to provide the structural engineering design for the Frame Apartments, a new 18-storey apartment development located at 111 Molesworth Street, Wellington.

As one of the city's tallest apartment buildings, the complex boasts a total of 54 one and two-bedroom apartments, including an exclusive roof top penthouse. In addition to the extensive performance and resilience requirements it was critical that the structure worked in harmony with the distinctive architecture which is intended to provide an enduring and distinctive landmark for the city.

Aurecon collaborated with architects Archaus and construct partner Arrow International to create a structural engineering solution that enabled the Frame Apartments to be built to the client's detailed requirements. At the core of the successful partnership was the creation of a common mind-set of collaboration and the establishment of an open and trustworthy work environment.

The earliest concepts of the building involved the careful assessment of numerous structural systems and building configurations. In addition to being exposed to Wellington's infamous winds, the significant seismic demands facing construction in the Capital and an increased focus on resiliency from prospective residents were key considerations.

The potential for wind sensitivity was highlighted as a critical design challenge requiring a blend of pragmatic and innovative solutions which helped form the selection of materials, as well as, the construction methodology itself. The final design incorporated an extruded exterior shear wall system which achieved both a unique aesthetic as well as a structurally efficient and economic construction.

The concrete structure provided the required combination of stiffness and resilience which could not effectively be achieved practically using any other materials and structural systems.

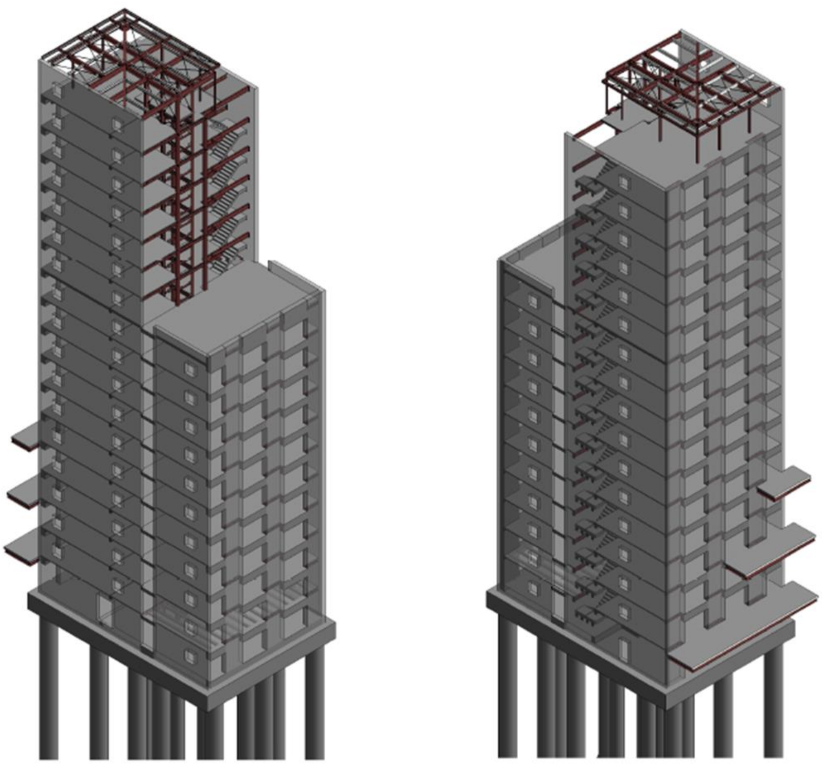


Figure 1: Isometric 3D-Model of the structure (North-West and South-East view respectively)

2 DETAILED DESCRIPTION OF THE STRUCTURAL DESIGN ELEMENTS

2.1 General Building Description

The building comprises of 11 and 18 levels of residential space in addition to ground level retail. The building plan is rectangular in shape with the 18 level tower located at the east end of the structure. The plan dimension for the building from ground to 11th level is approximately 19.5 meters long and 13.5 meters wide whereas above level 11 the length of the building reduces to 11.9 meters.

The structural lateral load resisting system is composed of reinforced frames on the East and West facades and pierced walls on the North and South facades, which are supported on bored concrete piles. The gravity system is composed of a Stahlton Rib floor supported on steel beams and concrete grouted steel columns.

The building structure supports the Client's project drivers with the shear wall layout and column and beam sizes being designed in order to increase useable floor area and maintain adequate clear headroom.

The structure was designed in compliance with the New Zealand Building Code (NZBC), section B1. The seismic analysis was principally conducted using the 3D computational software ETABS.

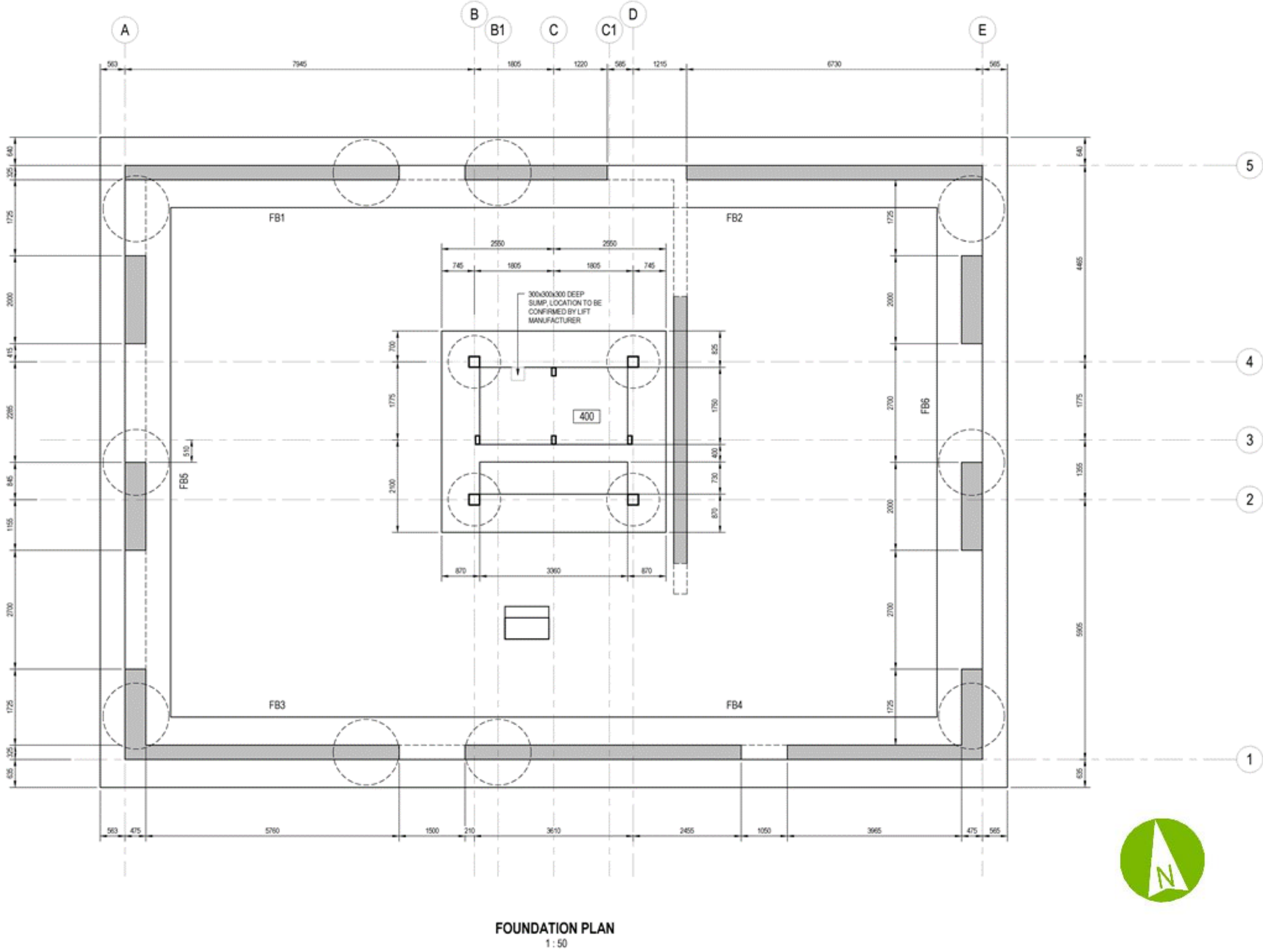


Figure 2: Plan of building foundations showing location of bored concrete belled piles.

2.2 Structural Principles

2.2.1 Primary Lateral Load Systems

2.2.1.1 West & East Frames

In the North-South Direction reinforced concrete frames with a beam sway mechanism provide the primary lateral load resisting system.

These frames have relatively deep 750 x 475 reinforced beams. It was established that minimum steel reinforcing provided a capacity sufficient to support a moderate ductility design.

2.2.1.2 North & South Walls

In the West-East direction lateral resistance is provided by 2 sets of reinforced shear walls.

These are essentially solid walls with relatively small penetrations in them. The depth of the "beam" beneath the openings is such that minimum reinforcement would force a hinge (if it were to form) at the base of the wall. As such the walls act essentially as cantilevers.

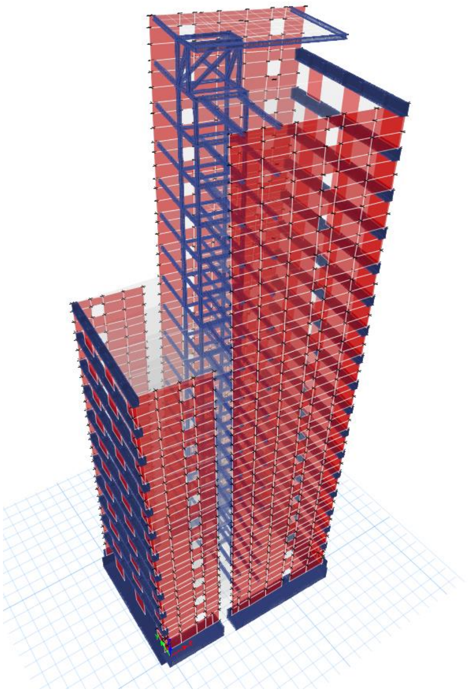


Figure 3: ETABS analysis model showing limited induced torsion.

Above Level 11 the structure steps in at the Western Façade. From this point onwards the façade is principally glazed. This presents a torsional demand which was anticipated and inherently accounted for in the 3D analysis modelling

The torsional actions are generally restrained by the relatively long North and South walls. A jump in the demands either side of the transition was found to normalise within a few stories. The amount of torsional deflection or twist in the structure was found to be relatively small given the stiffness of the North and South walls.

Given the length of the walls they are relatively strong and will essentially remain elastic under the design Ultimate Limit State (ULS) loading. For the structural design this proved problematic, particularly in regards to excessive pile demands and story shears which would have required very deep founding depths and heavy reinforcing when considering a typical capacity design methodology. As such an alternative inelastic mechanism was introduced at the pile to ground beam interface whose over-strength tension capacity limits the maximum actions that the walls can be subjected to. This mechanism is described in more detail in Section 2.2.1.4.

2.2.1.3 Diaphragms

A reinforced in-situ topping on top the Stahlton Ribs provides rigid diaphragms at each floor level to distribute lateral loads to the shear walls and frames. The shear walls and frames are founded on concrete bored piles tied together through a series of ground beams.

2.2.1.4 Tie Beam – Pile Tension Interconnection

The slender aspect ratio of the building which led to the introduction of the rigid concrete exterior walls results in excessive seismic uplift and flexural demands, particularly when considering over-strength capacity design actions. In order to alleviate the full magnitude the this design force, as well as provide additional resilience to the superstructure, the connection between the piles and ground beams on which the walls and columns are founded have been designed to allow yielding at this interface, and thus become the "fuse" that protects both the remainder of the pile and the North - South walls. This reinforcing bar fuse connection is illustrated in Figure 4.

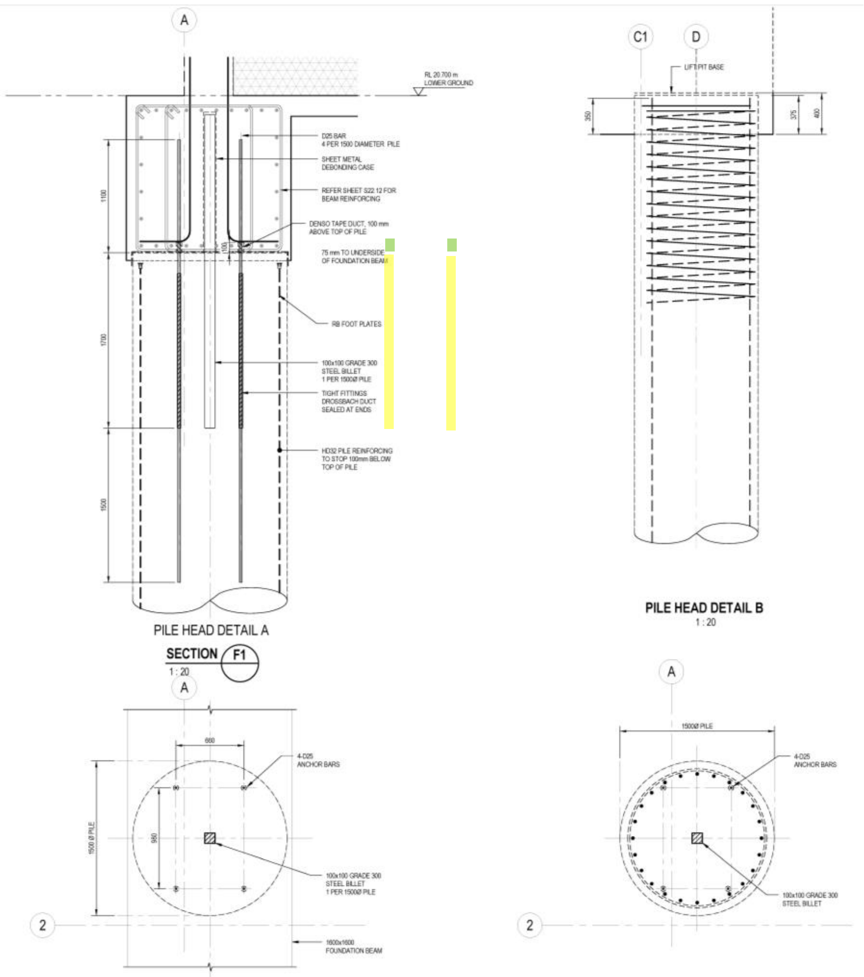


Figure 4: Detail showing "fuse" which was introduced to limit design actions in the piles and upper superstructure. (Yellow highlight indicates Drossbach ducts used to de-bond the reinforcing. Green highlight indicates top of Drossbach duct wrapped in Denso tape to prevent binding)

To reduce the maximum strain in the yielding elements the reinforcing bars were de-bonded over a length of 1.7m. Within the top of the pile a tight fitting Drossbach Duct was specified (highlighted yellow in figure XXX). In order to avoid excessive spalling at the interface of the pile and reduce the risk of bar buckling and localised high stresses at the joint the Drossbach duct was extended 100mm above the top of the pile and wrapped in Denso Tape in order to avoid binding. A steel billet was placed at the centre of the pile to provide a shear key. A sheet-metal case envelopes the top of the billet to prevent any axial load transfer.

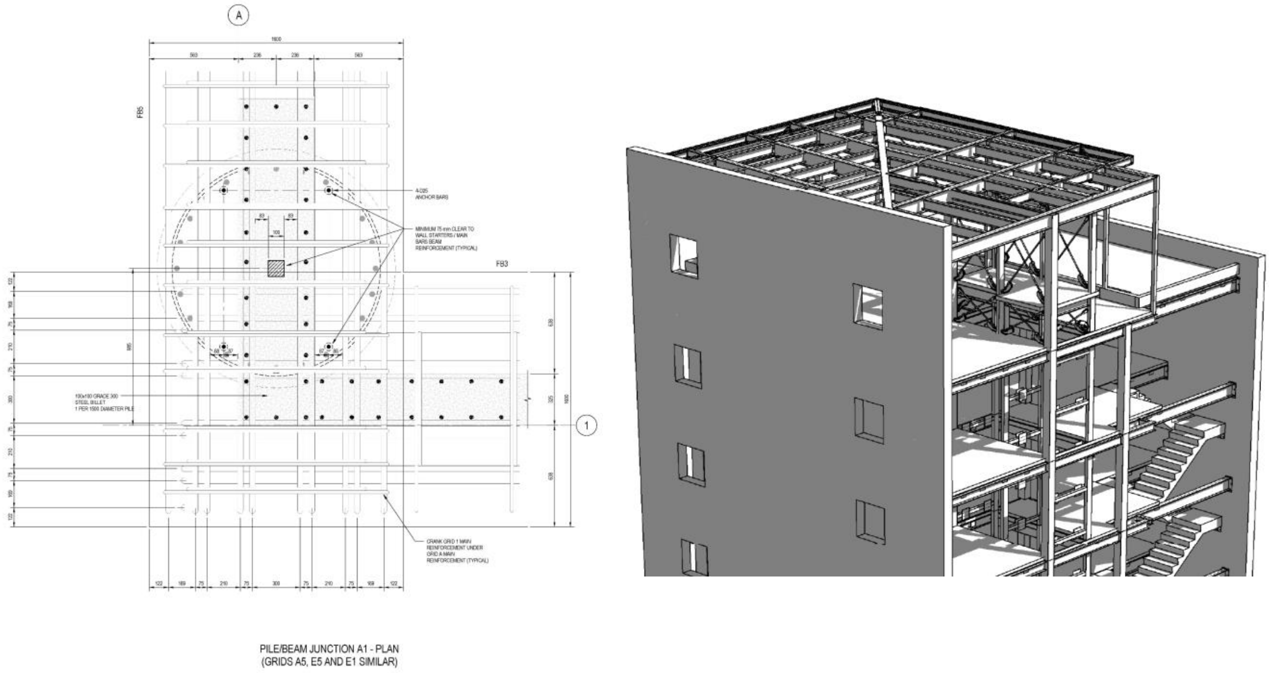
Careful detailing of the pile to ground beam interface was critical to ensure both constructability, as well as, to help validate that the mechanism specified would perform as intended. Comprehensive details and 3D models of these critical areas were drafted in Revit, such as illustrated in Figure 5, to verify the buildability of the proposed structural design.

2.2.2 Gravity Load Systems

Suspended concrete slabs transfer loads to steel beams which are supported on columns and shear walls/frames supported by ground tie beams and bored concrete piles.

2.2.2.1 Foundations

The foundation system consists primarily of ground tie beams that are supported on bored belled concrete piles. The nominal diameter of these piles ranges from 1.2m - 1.5m, with the bell diameter increasing up to 2.8m. The piles were typically founded at a depth between 20m - 25m.



(a) *(b)*

Figure 5: Fully detailed sections and renders modelled in 3D with Revit. Including all structural elements was a valuable asset during construction, structural steel and precast fabrication, and clash detection. (a) Shows reinforcing layout of ground beams, pile, and wall reinforcing. (b) Shows a full 3D render of the top of the building including penthouse framing, elevator secondary steel, and precast stair elements.

2.2.2.2 Ground Floor Slab

The ground floor slab was designed as a 200mm thick cast-in-situ reinforced concrete diaphragm tied to the ground beams. The ground slab extends over the entire structural footprint and acts as a rigid diaphragm together with the ground beams to tie the piles together and to distribute base shear.

2.2.2.3 Suspended Slabs

The suspended floor slabs consist of a mixture of 150mm and 125mm Stahlton Ribs at 900c/s supporting a reinforced 90mm thick concrete topping. The floor ribs are supported on top of structural steel gravity beams and columns. Mild steel reinforcing bars connect the floor slab diaphragms to the shear walls, through threaded cast-in Ancon couplers. At Level 11 the thickness of topping is increased to 150mm to provide the necessary diaphragm capacity to resist the increased forces from the change in floor configuration.

2.2.2.4 Balconies

The residential balconies are located at Levels 1, 3 and 5, reducing in size with height up the building. The design primarily utilises cantilevering 310UB and 310UC structural steel sections spaced at 1.2m centres. These are anchored through cast-in weld plates to the Eastern exterior wall. The decking consists of lightweight timber framing, and barrier/handrails are proprietary. Careful consideration was given to vibration control, as well as, ease of erection given the requirements of working at height.

2.2.2.5 Penthouse

The top level of the apartment building consists of a single level penthouse structure. The structural system incorporates structural steel framing with Reidbrace cross-bracing providing lateral support. The Northern exterior reinforced concrete wall extends up to the penthouse level also provides lateral bracing to the light weight structure.

Figure 6: Rib-Infill floor prior to installation of topping diaphragm. The floors were installed following construction of the exterior walls and connected via cast-in Ancon threaded couplers.

3 SOIL CONDITIONS

3.1 Description of Site Soil Conditions

A geotechnical assessment of the site was produced by the Aurecon in May 2016 expanding on an existing report on the subsoil class produced by RDCL in June 2014. The site subsoil category in terms of NZS 1170.5:2004 Clause 3.1.3 was designated as class C for seismic response.

An ultimate end bearing strength for the piles of q_u = 4.0 MPa was specified where founded on dense gravels. Shear friction values of up to 95kPa were achieved at increasing depths.

The soils were considered to have a very low risk from liquefaction as per the Geotechnical reporting.

4 DESIGN CRITERIA

4.1 General

The structural design was designed in accordance with the New Zealand Building Code, and the respective design and material standards associated with this.

The building design life for the primary structure (floor and foundations, walls and structural framing and roof structure) is defined to be 50 years as per the requirements of the Building Code.

As per AS/NZS 1170.0 clause 3.3, the building is considered to be an importance Level 2 structure, and as such was designed considering an ultimate and serviceability earthquake and wind loading demand corresponding to the 1/500yr and 1/25yr events respectively. A maximum considered earthquake demand of x1.8 the ultimate demand was considered in the design.

4.2 Seismic Loads and Analysis

The seismic analysis was primarily based on the force based Response Spectrum methodology as defined in NZS1170.5. In addition, Displacement Based Design verifications were also completed to ensure that the design displacements were compatible with the curvature limits in the main frames and wall elements.

The NZS 1170 Seismic Design Coefficients are given as the product of spectral shape factor (a function of building period and site subsoil class), the site hazard factor, near fault factor and the return period factor (as a function of the building design life and importance category).

The soil classification was confirmed by the geotechnical findings to be Soil Type C

The Site Hazard Factor (Z) for Wellington CBD is 0.4.

In addition, the 2016 7.8 Kaikoura earthquake occurred during the time when the existing building on the site was in the process of being demolished. Apparent basin edge effects that were noted in the surrounding areas local to the site were considered during the detailed design phase of the project. This included a review of the spectral peaks recorded at nearby strong-motion stations in relation to the expected structural periods.

4.3 Seismic Design Principles

The seismic design was based on the response associated with upper bound pile stiffness demands considering a ductility of $\mu = 3.5$ in the West-East frames and 3.0 in the North-South walls both with Sp = 0.7. Consideration was given to variable structural behaviour based on the sensitivity of upper, lower and nominal pile stiffness properties.

An important consideration in establishing the ductility demand was to ensure that the capacity design shears in the beams did not require the use of diagonal reinforcement, which would have significantly increased the complexity of the detailing and slowed construction. In addition, the level of ductility was intentionally set below the maximum values at which analysis showed that P-Delta effects would need to be considered (ie the calculated stability co-efficient is less than 0.1).

As discussed in Section 2.2.1.4 the connection between the piles and the tie beams on which the walls and columns are founded were designed to allow yielding at this interface and thus become the fuse that protects both the remainder of the pile and particularly the North-South walls from over-strength actions.

Capacity Design principles were used to determine the maximum design actions in the North and South shear walls based on the maximum over-strength capacity of the tension connection. For actions scaled to $\mu = 1.5$, Sp = 0.87 all of the piles associated with the North-West and South-West walls developed net tension demands in excess of the over-strength capacity of the hold-down connection. This load combination was therefore used as an upper bound to the actions that could be developed based on the over strength capacity of the yielding mechanism.

Based on iterative analyses 4-D25 tie bars in the 1500 mm diameter piles were selected, these have a reliable tension strength of 500 kN. When the analysis results are scaled to the design ductilities specified the most critical tension connection is at its yield point.

5 INNOVATION IN CONSTRUCTION

Arrow International was engaged on the project from the initial concept phase and played an active part in developing the design of the building. They were able to take advantage of their expert input and accumulated knowledge to deliver an economic and efficient construction programme.

An example of innovation brought to the construction, at least in a New Zealand context, was the use of an jump-formwork system in constructing the exterior reinforced concrete walls. This system and erection methodology allowed multiple storeys to be constructed before craning in the rib-and infill precast floor system and internal framing. It allowed the external walls to be constructed without interference to the inside of the building. Given the tight constraints of the site there was little room for the storage of materials, therefore the ability to cast the walls and lift the formwork without interference to the inside of the building allowed for great efficiencies, quality control, and reliably to meet a challenging construction programme.

The reusable formwork system also meant less waste on site as the single system kept climbing skywards as construction progressed. So reusable and efficient it is, that the same formwork is now being used by Arrow on a different building project in New Zealand. The accuracy of the formwork meant that concrete wastage was drastically reduced compared with a traditional concrete building, and as each level progressed workers had a readymade secure platform to work internally from.

Figure 7: Jump-formwork system in action. Walls are cast a number of levels in advance of the rib-and infill floor installation. Part of the system includes a safe and secure platform for workers.

6 REALISING THE ARCHITECTURAL INTENT WITH THERMAL MASS

Whilst this concrete exterior wall was structurally efficient and economical to build, it served an aesthetic and architectural intent in that the internal concrete walls would be visible to residents and part of the appeal in purchasing an apartment. While the developer had used clear finished precast concrete for party walls previously, it wasn't until the design team came up with the concrete walled option, that it was envisaged that the insulation could be applied to the exterior of the building which would let the occupants "see" the concrete internally. The exposed concrete walls became the visible feature of the development, with the colourful panels visible on the exterior providing additional insulation.

This form of construction also utilised the concrete's thermal mass as part of an overall passive solar design, which will help to minimise future heating and cooling demands, and in turn boost health and wellbeing.

7 AN AWARD-WINNING STRUCTURAL SOLUTION

Figure 8: The recently completed Frame Apartments.

Aurecon knew that an innovative approach was required and that not only was the construction method important, so were the construction materials.

The resulting reinforced concrete structure provided the required combination of stiffness and resilience, with a construction method design that minimised material wastage and build time. The structure was also rigid enough to withstand high winds and durable enough to withstand unexpected seismic events.

The sustainable use of concrete was recognised at the 2018 Concrete Sustainability Awards where the project took out the Excellence in Residential Concrete Construction Award 2018. The concrete solution was praised for its rapid in-site construction and the associated advantages of robustness and resilience. The judges commented on how the approach would no doubt gain greater uptake as the need for medium-density housing continues to grow in response to a growing population in New Zealand's major centres.

8 REFERENCES

Aurecon NZ Ltd. 2016. *111 Molesworth Street Frame Apartments - Geotechnical Report*, Revision 1

Aurecon NZ Ltd. 2017. *111 Molesworth Street Frame Apartments – Structural Engineering Design Features Report Geotechnical Report*, Revision 4