Transactions on Engineering and Computing Sciences - Vol. 12, No. 2
Publication Date: April 25, 2024
DOI:10.14738/tecs.122.16501.
Wong, S., Heng, K. H., Maey, L. G. M., & Tan, T. H. (2024). Case Study: The Use of Concrete Prefabricated Prefinished Volumetric Construction (Ppvc) For the World Tallest Two Blocks of 56-Storey Residential Towers in Singapore. Transactions on Engineering and Computing Sciences, 12(2). 174-194.

Case Study: The Use of Concrete Prefabricated Prefinished Volumetric Construction (Ppvc) For the World Tallest Two Blocks of 56-Storey Residential Towers in Singapore

Wong, Seng
TW-Asia Consultants Pte Ltd

Heng, Kim Huat
TW-Asia Consultants Pte Ltd

Maey, Leow Geok Mui
TW-Asia Consultants Pte Ltd

Tan, Teng Hooi
Singapore University of Social Sciences (SUSS)

ABSTRACT

In an effort to minimize dependence on foreign labor and enhance productivity in the construction sector, Singapore's building industry is urged to adopt the Design for Manufacturing and Assembly (DfMA) approach, which shifts a significant portion of construction activities to an off-site, controlled manufacturing setting. The Prefabricated Prefinished Volumetric Construction (PPVC) method, a notable example of such technology, markedly reduces the need for on-site labor and accelerates construction processes. This paper discusses the pioneering use of a patented reinforced concrete composite structural wall system in erecting two 56-story residential towers, featuring an innovative approach where adjacent PPVC modules are connected by self-levelling concrete, resulting in a robust combined wall system. Through prototype testing, including compression and shear tests, the effectiveness of this system under various stresses was confirmed, making this development a landmark in the use of reinforced concrete modular construction for high-rise residential buildings. The project saw the final PPVC module installed in January 2022, leading to a Temporary Occupation Permit by March 2023.

Keywords: prefabricated prefinished volumetric construction, reinforced concrete composite structural wall system.

INTRODUCTION

The Avenue South Residence (Fig. 1) is a residential high-rise development at Silat Avenue (Fig. 2), Singapore. It is developed by United Venture Development (SILAT) Pte Ltd, a joint venture of UOL Group Ltd, United Industrial Corporation (UIC) and Kheng Leong Co Pte Ltd. The project comprises two tower blocks of 56-storey apartments with ancillary landscape, a swimming pool and communal facilities at ground level. A multi-storey car park is included with a basement level linking the two towers. In total, there are 505 residential units in the development.



Fig. 1: Project Perspective

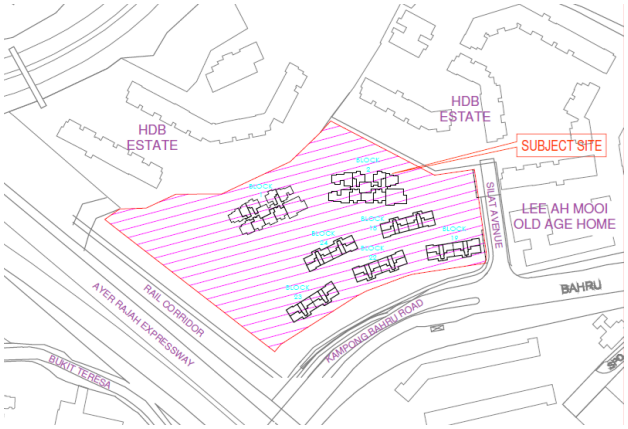


Fig. 2: Site Location Plan

To further enhance construction productivity, the Singapore Urban Redevelopment Authority (URA) encourages the building industry consultants and builders to construct higher-level building using Prefabricated Prefinished

Volumetric Construction (PPVC) technology, which is an advanced and highly productive construction methodology that speeds up construction works significantly.

The Avenue South Residence has adopted the reinforced concrete PPVC system for the two tower residential blocks in accordance with the requirements outlined in the Singapore Building Construction Authority (BCA)'s Code of Practice on Buildability 2015 [2]. Design of the reinforced concrete PPVC modular system was undertaken by the Civil & Structural consultant, M/s TW-Asia Consultants Pte Ltd.

With support from BCA and working in tandem with the builder, TW-Asia Consultants Pte Ltd has pioneered the design of the reinforced concrete PPVC technology using its patented Composite Structural Wall system under the European Patent no. EP3263795 entitled "Composite Structural Wall and Method of Construction Thereof". It was through research,

testing and continual development that this unique structural wall system was devised as the key technical component for the PPVC system.

The Avenue South Residence is the tallest building project in the world adopting the reinforced concrete PPVC modular system when its last module was installed in January 2022. Some salient project data and records are shown in Table 1 and 2 below:

Table 1: Project Data

Site area	22,851.60m^2
Proposed GFA (including bonus balcony & PES GFA): y	92,876m^2
Proposed gross plot ration (including bonus balcony & PES GFA):	3.70
No. of tower block	2
Total no. of storeys	56
Proposed building height(m) AMSL:	200m
Typical storey heigh:	3.15m
Total no. of residential unit:	988
Project contract period:	36 months
Contract commencement date:	16 August 2018
Project TOP (Phase 1 – tower blocks/podium/E-deck)	27 Mar 2023

Table 2: Project Timelines and Records

Piling commencement	Jan 2019
PPVC module installation commencement	Feb 2020
Covid-19 lockdown	April – July 2020
Tower 1 PPVC completion of module installation	27 Nov 2021
Tower 2 PPVC completion of module installation	11 Jan 2022
PPVC installation duration	18 months
Floor cycle	8.4 days (average)
Total PPVC modules	3,034
Module weight	30+ tonnes
Safety Record	750,000-man hours

ARCHITECTURAL CONSTRAINTS

As part of the planning design requirement, pocket sky gardens and a refuge floor (Fig. 3a & 3b) are required to be provided in the two towers as follows:

- 16 nos. of pocket gardens at different levels of the towers
- Refuge floor at 36th storey of the towers

These constraints have resulted in the discontinuity of PPVC module adoption at these floors/areas. Consequently, this has impacted the construction efficiency & productivity as these affected areas are constructed in conventional in-situ methods which are more labour intensive.

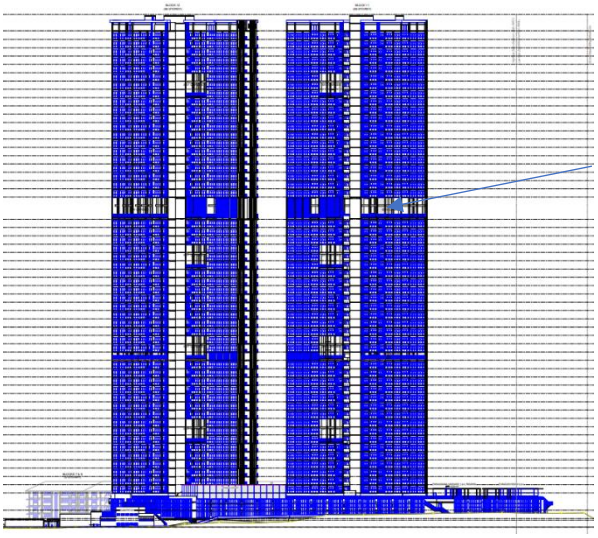


Fig. 3a: Pocket gardens and refuge floor



Fig. 3b: Close-up view of pocket gardens

STRUCTURAL SYSTEM

The structure primarily consists of two 56-story towers, featuring two basement levels and a two-story car park podium, grounded on bored pile foundations. The substructure uses a pile raft for the lower basement, while upper levels incorporate a flat slab design. The third story uniquely employs a beam slab construction. For the tower blocks, a reinforced concrete (RC) PPVC modular approach covers at least 65% of the floor space, adhering to BCA's Buildability standards. The remaining areas, chiefly corridors, use traditional precast or in-situ RC beams and slabs, ensuring structural integrity by distributing lateral forces to the core. walls.

PPVC SYSTEM

PPVC Module – Weight Constraint

The composite shear walls have a total thickness of 300mm, enhancing the building's ability to withstand lateral forces like wind and notional loads by providing necessary stiffness. To facilitate easier handling and transport, the walls of each module are designed to be 100mm thick. A 100mm space between the walls of adjoining modules is then filled with self-levelling

concrete directly at the construction site to achieve the desired stability and structural integrity.

PPVC Modularisation

The dimensions of PPVC modules are determined by local transport limitations and the lifting capacity of construction cranes. To comply with road transport regulations and eliminate the need for police escorts, modules are designed to fit within a 3.4m wide transport vehicle. Height restrictions are also considered to ensure modules can safely pass under bridges and gantries with a 4.5m clearance. Effective site management is crucial for the delivery, storage, and installation processes. For optimal efficiency, PPVC modules should be rectangular, with uniform wall thicknesses and aligned walls. The Avenue South Residence project utilized 3034 PPVC modules across its two towers.



Fig. 4: Tower 1 & 2 PPVC Modularization Plan

PPVC Concrete Carcass Components

A typical PPVC concrete carcass (Fig. 5a & 5b) comprises two structural shear walls, a floor slab, a non-structural ceiling slab and non-structural end wall with window opening. The M&E services conduits and pipes are embedded in the floor slab, ceiling slab and walls of the module.

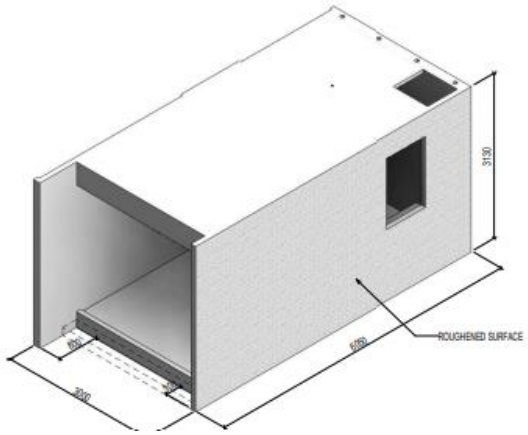


Fig. 5a: Typical PPVC concrete carcass

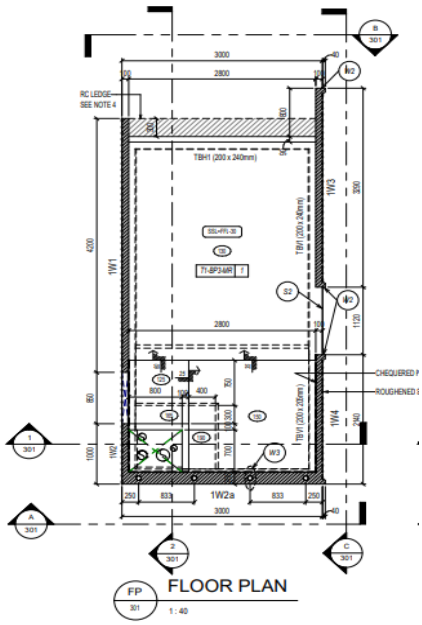


Fig. 5b: Typical PPVC module floor plan

Floor Slab

The reinforced concrete (RC) floor slab extends to the walls of the module, acting as a horizontal diaphragm. This structure is crucial for transferring lateral forces to the core walls of the lifts and staircases, ensuring stability against movements such as wind or seismic activity.

Ceiling Slab

The ceiling slab serves a non-structural role, enhancing the module's stiffness and providing support to the walls during transport and installation. Additionally, it functions as a platform for workers during the assembly of the module.

RC Walls

The structural reinforced concrete (RC) walls are strategically positioned along the longer sides of the modules, tasked with supporting both the ceiling and floor slabs.

Upon installation, these walls are linked with those of neighbouring modules through reinforcements set in self-levelling concrete at the joints, creating a unified composite structural wall. This integrated wall system is engineered to function cohesively under both compression and bending forces, making every module wall an essential component of the building's overall lateral force resistance mechanism.

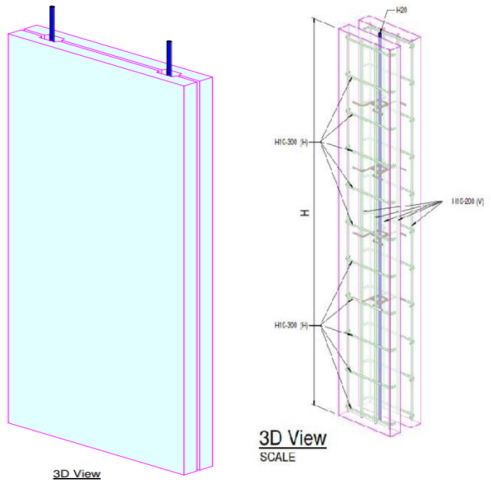


Fig. 6: Composite shear wall system

Horizontal Floor Diaphragm

Horizontal floor diaphragm action is achieved by connecting the adjoining PPVC modules' walls and slabs together with in-situ concrete & reinforcement. The linking modules are connected to the in-situ floor slabs and lift/storey shelter core walls with adequate reinforcement anchorage.

Module Typical Connection Details

Vertical and horizontal ties are provided across adjoining modules. Typical connection details of PPVC modules are shown in Fig. 7a & 7b below:



Fig. 7a: Floor slab connection between modules

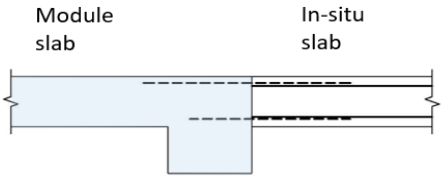


Fig. 7b: Module floor slab connection to in-situ slab

TOWER LATERAL LOAD PERFORMANCE

Wind Tunnel Test

Wind tunnel test (Fig. 8a to 8c) had been carried out to obtain more accurate estimates of the wind-induced structural loads, load effects and building motion of the two tower blocks.

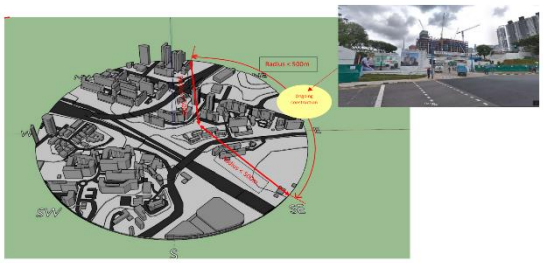


Fig. 8a: Proximity plan

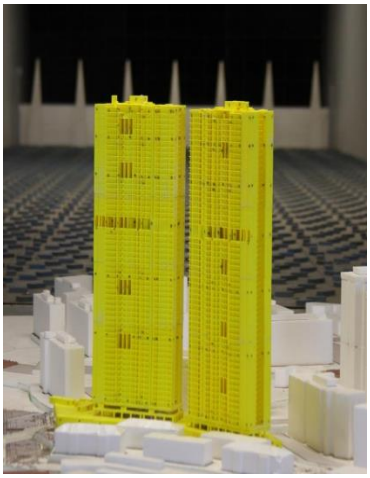


Fig. 8b: Wind tunnel test model (close-up view of towers)



Fig. 8c: Wind tunnel test model (overall view)

The results of the wind tunnel study indicate that the one-year return period peak building acceleration & rotational velocities and the five-year period standard deviation building satisfy the relevant published occupant comfort criteria for wind-induced building motions.

Lateral Analysis

ETABS software has been used to model the performance of the tower blocks under lateral load (Fig. 9). The building's top displacement and inter- storey drift ratios are controlled to be less than 1/500 and the ETABS results show that the tower structures perform satisfactorily.

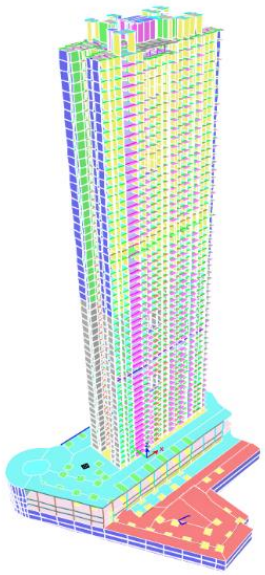


Fig. 9: Etabs analysis model

The performance of the towers under wind loads are shown in Table 3 & 4 below:

Table 3: Lateral displacement under wind action

Lateral Displacement	Block 1/2
Total building top displacement ration, **δ /** H	1/652 ≥ 1/500
Inter storey drift ration, **δ** / h	1550 ≥ 1/500

Table 4: Mode shape – time period (s)

Mode	Block 1/2
1 (Translational)	7.2
2 (Translational)	6.6
3 (Torsional)	6.1

Based on the ETABS results:

- Along the major axis of the PPVC composite shear walls ~ 85% of wind is carried by the walls
- Along the minor axis of the PPVC composite shear walls ~ 30% of the wind is carried by the walls

Tower Robustness

The robustness of the tower blocks has been evaluated to ensure they can withstand notional horizontal forces. This assessment ensures each block can resist a theoretical ultimate

horizontal force at every floor or roof level, amounting to 1.5% of the structure's characteristic dead weight, spanning from the mid-height of one story to the next. This approach adheres to local design standards. Additionally, structural reinforcements including horizontal and vertical ties are implemented and verified for compliance with these standards.

DURABILITY

The structures have been designed to Structural Class S4(Design working life of 50-years) with Exposure Class XC3(Corrosion induced by carbonation - moderate humidity) to local design standards.

FIRE RESISTANCE

The structures have been designed for a fire resistance of 1.5 hours. Fire compartmentalization is achieved by separation of floor slabs, separation of vertical compartments by RC walls or rated partitions and plumbing risers located within the PPVC units. Horizontal compartmentalization is maintained with the risers segmented into separate compartments at each floor.

PPVC WALL PROTOTYPE LOAD TESTS

Prototype tests had been carried out to study the behaviour of the sandwiched composite wall under the actions of compression and bending.

Compression Test

The objective of the prototype compression load test was to verify whether the composite wall sample could withstand the design load in a composite manner (Fig. 10a to 10c). The compression test was performed in a local university where it was loaded up to 4648kN, more than 14% the design ultimate load of 4080kN. The wall was observed to be able to sustain the design ultimate load without failure. At the final ultimate failure, there was no delamination observed at the RC concrete wall panels/in-fill concrete interface as shown in Fig. 10b. The failure mode was essentially a compression failure at the top and the base of the specimen. The test shows that the test sample had performed satisfactorily under compression in a composite manner.



Fig. 10a: Module compression test



Fig. 10b: Close-up view of compression test at failure

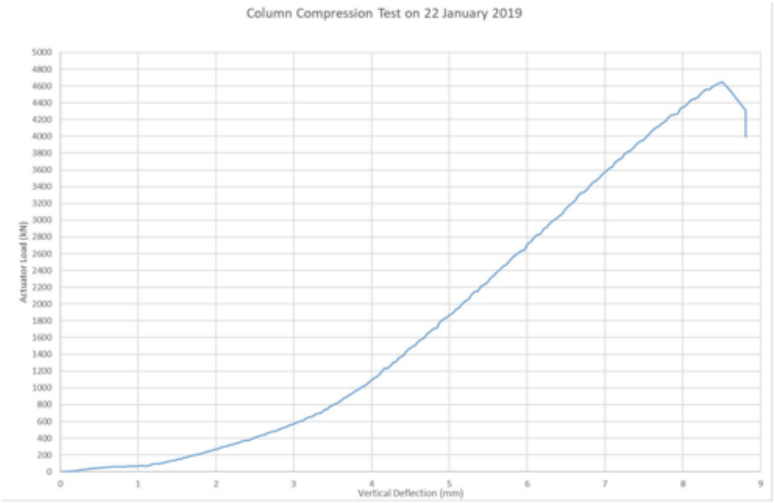


Fig. 10c: Load-deflection behavior

PPVC CONCRETE CARCASS FABRICATION

3-D fabrication method (Fig. 11a to 11c) was adopted for the casting of the module concrete carcass in Johor, Malaysia. The following critical activities and checking were carried out in the precast factory:

- Precast steel mould shall be rigid and stable with proper facilities to adjust dimensions. Module dimensions shall be checked after mould assembly and after demoulding for continual usage
- After casting, the complete module shall be double checked for dimensions, verticality and levels to ensure that they are within the tolerances to minimize any impact to the gross floor area (GFA) and net usable space
- M&E services embedded in the concrete carcass must be coordinated properly and accurately with the adjacent modules so that module connections on site will be accurate

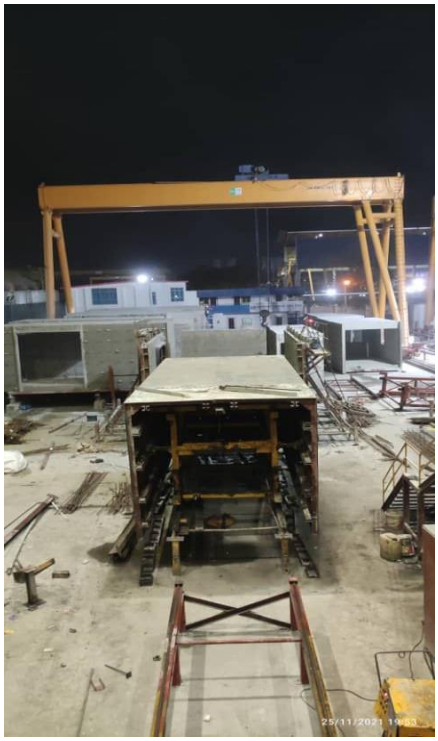


Fig. 11a: 3-D module fabrication



Fig. 11b: Storage of completed modules in precast factory

PPVC FIT-OUT WORK

The completed PPVC concrete carcasses from Malaysia were delivered to a fit-out factory in Singapore. The level of finishing and fittings to be completed off-site are as per Table 5 of the Code of Practice on Buildability 2015 [2] as follows:

Table 5: Level of finishing and fittings to be completed off-site

Element	Minimum level of completion off-site
Floor finishes	80%
Wall finishes	100%
Painting	100% base coat, only final cost is allowed on-site
Windows frame and glazing	100%

Doors	100% only door leaves allowed for on-site installation
Wardrobe and cabinets	100% only wardrobe and cabinet doors allowed for on-site installation
M&E including water & sanitary pipes, electrical conduits & ducting	100% only equipment and fixtures allowed for on-site installation
Electrical sockets and light switches	100% only light fittings allowed for on-site installation

In the fit-out factory (Fig 12a & 12b), architectural finishing (floor finishes, wall finishes, painting, window frame and glazing (Fig 12c), doors and wardrobe and cabinets) and M&E fit-out works (water & sanitary pipes (Fig 12d), electrical conduits and ducting, electrical sockets and light switches) were installed. This maximised building productivity. Water-proofing works were also carried out in the fit-out factory to check for water-tightness at the wet areas before laying floor tiles. Proper protection to fit-out works in the modules was carried out before delivery to site for installation (Fig 13a & 13b).

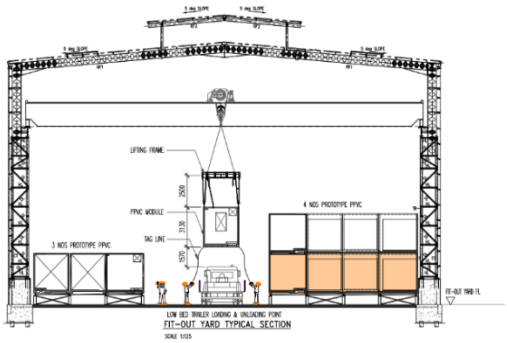


Fig. 12a: Fit-out factory – typical section



Fig. 12b: Modules in Fit-out Factory



Fig 12c: Architectural & M&E fitting out in progress



Fig 12d: Piping works fitting-out factory.



Fig 13a: Protection to module door frames & flooring



Fig 13b: Protection of module before delivery to site

PPVC INSTALLATION ON SITE

Upon arrival at the site, the modules are raised to their precise locations using a specialized tower crane designed for heavy loads and equipped with a self-regulating lifting mechanism. The primary installation challenge involves mitigating the sway of these modules caused by wind at elevated heights. This task necessitates a highly skilled crane operator who ensures the modules are elevated and positioned with great care to prevent any tilting. Additionally, the concrete slab that receives the modules must be thoroughly inspected for level accuracy, with necessary adjustments made using shim plates. The placement of the modules is guided by the gridlines surveyed and marked on either the receiving slab or the top slab of previously installed modules.

Tower crane location & lifting coverage analysis have to be planned in advance so that it is suitably positioned considering the reach and lifting capacity (Fig. 14a & 14b). The logistic route/space of module delivery, off-loading and temporary storage on site must also be taken into consideration for smooth delivery, lifting & final installation.

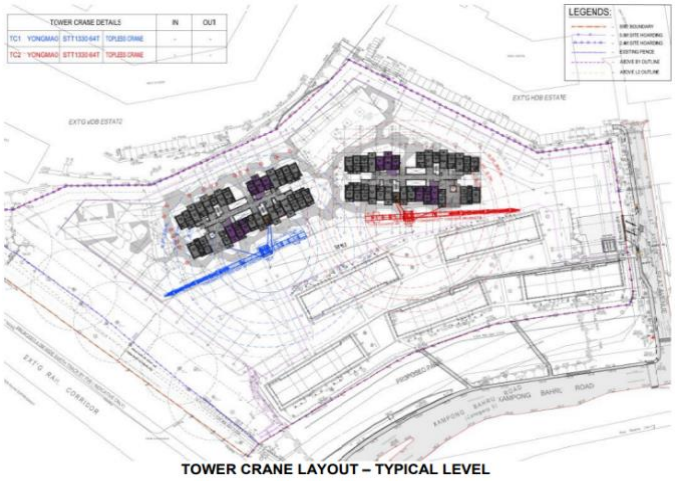


Fig. 14a: Tower crane positioning for lifting

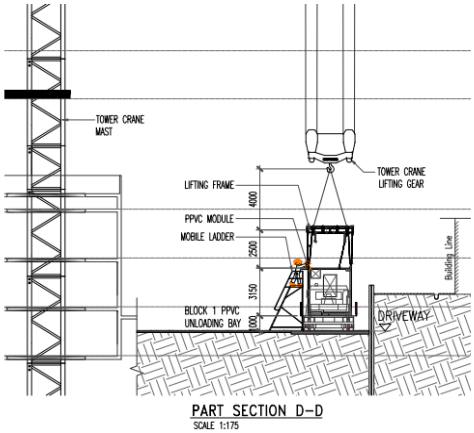


Fig. 14b: Tower crane positioning & lifting



Fig. 15a: Hoisting of PPVC Module



Fig. 15b: Module installation

Backer rods were installed at the gaps between the ends of adjoining module walls; patched up with mortar to prevent grout loss during in-situ joint grouting. Upon installation of the modules, vertical linking bars were installed at the gaps between the adjoining modules and filled with self-levelling concrete to create the required composite structure wall system. The PPVC modules were also connected to the adjoining in-situ floor structures and the lift/storey shelter walls. M&E services between the adjoining modules were connected; light fittings, equipment & fixtures were installed. Final Architectural activities: floor finishes, painting, door leaves, wardrobe, cabinet doors were also completed during this stage. External water seepage control at the PPVC modules end joints generally comprises applying a layer of fibre mesh and cementitious water-proofing membrane.

For this project, the total duration of PPVC module installation was approximately 18 months; with the floor cycle time from six to nine days. Understandably, the first two to three floors took a longer cycle time as they were in the initial learning curve of installation.

M&E SERVICES IN MODULES

M&E Services (Fig. 16a to 16d) in a typical PPVC module generally comprise the following

- Vertical stacks used for sanitary pipes

- Connection of vertical pipes is doing using hubless C.I. pipe fittings or uPVC loose socket fittings
- Water distribution pipes crossing between module
- Electrical cables crossing between modules using junction boxes

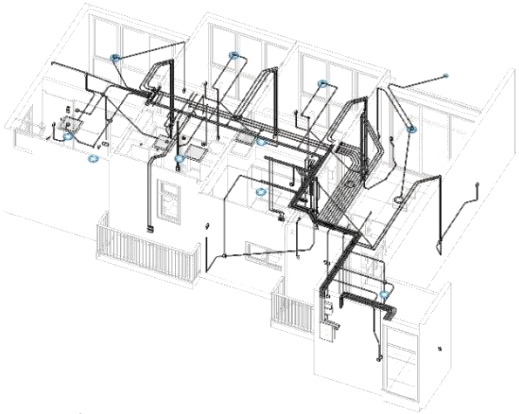


Fig. 16a: Electrical services

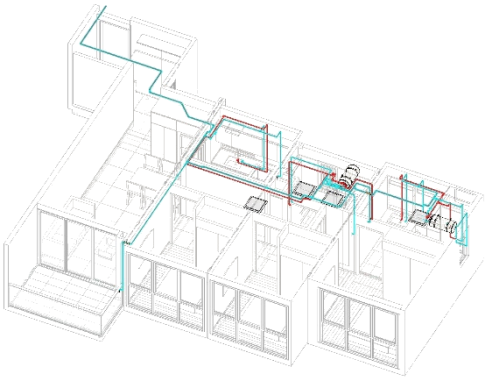


Fig. 16b: Plumbing services

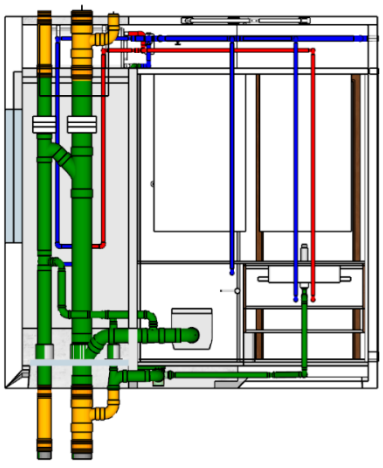


Fig. 16d: Typical in-built bathroom

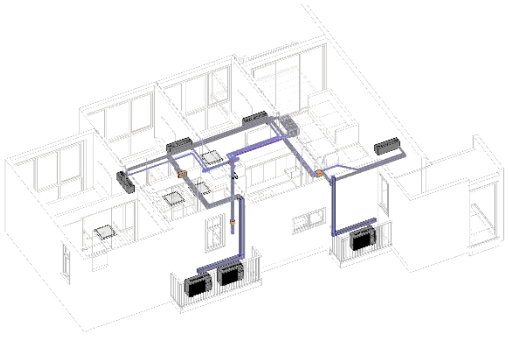


Fig. 16c: ACMV services

TRANSPORTATION & LOGISTICS

Given the project's magnitude, it's critical for the contractor to meticulously plan and coordinate transportation and logistics. This planning ensures a seamless flow of modules from the precast fabrication and outfitting phases to the final installation on site.

- Fabrication of PPVC concrete carcass including embedded M&E services at precast factory
- Architecture and M&E finishing & fittings to the PPVC modules at fit-out factory
- Installation of PPVC modules on site

It is important that during the initial design stage, dimensions of modules are carefully planned and adopted with consideration of the following local roadway constraints (Fig. 17 and Table 6):

- Overall transportation weight not exceeding 3.4m or
- Overall transportation weight less than 80 tonnes or
- Overall transportation height not exceeding 4.5m

Any deviation to the above will require auxiliary police escort which will incur additional cost.

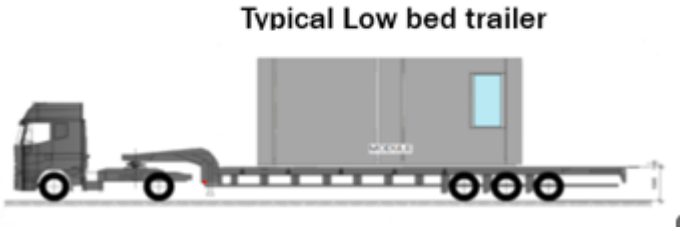


Fig. 17: Typical low bed trailer for module delivery

Table 6: Transportation delivery roadway constraints

	Typical Trailer size	LTA Guidelines without police escort
Length	16.95 m	No limit
Width	3.05 m	< 3.4 m
Height	4.30 m	< 4.5 m

BUILDABLE DESIGN & CONSTRUCTABILITY SCORE

Based on local guidelines in BCA's Code of Practice on Buildability 2015, by adopting the PPVC technology, this project has achieved a marked improvement in the Buildability and Constructability Score. The total Buildable Design Score achieved is 94, which is higher than the minimum required score of 88. The total Constructability Score is 64, which is higher than minimum required score.

PROGRESS PHOTOS

Some project progress photos (Fig. 18a to 18d) are shown below:



Fig.18a: Work commencement in January 2019



Fig. 18b: Commencement of PPVC module installation



Fig. 18c: Completed Tower View (TOP March 2023)

The module installation dates are shown in Table 7 below:

Table 7: Module installation date on site

Tower No.	First module installation	Last module installation
Tower 1	10th February 2020	27th November 2021
Tower 2	17th July 2020	11th January 2022



CONCLUSION

This project has successfully implemented the RC Composite Shear Wall System as the PPVC technology in the construction of the two 56- storey residential towers in Singapore.

Advantages realised from the adoption of PPVC system in this project were as follows

- Improved productivity and hence early project completion

- Improve site safety as on-site activities are reduced tremendously
- Improved quality of end product as most activities are done in a factory-controlled environment
- Vast reduction in noise & dust pollution at job site

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the involvement and support of all the project team members who have contributed one way or another to the successful completion of this project.

References

[1] Design for Manufacturing and Assembly (DfMA) – BCA Publication

[2] Code of Practice on Buildability 2015 Edition – BCA Publication