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REACHING NEW HEIGHTS IN THE USE OF CONCRETE PREFABRICATED PREFINISHED VOLUMETRIC CONSTRUCTION (PPVC) : TWO 56-STOREY RESIDENTIAL TOWERS IN SINGAPORE

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Abstract

To reduce the reliance on foreign workforce and raise construction productivity, the Singapore building industry is encouraged to embrace the concept as per Design for Manufacturing and Assembly (DfMA) [1] whereby a substantial portion of construction works is done off-site in a controlled manufacturing environment. Prefabricated Prefinished Volumetric Construction (PPVC) modular system is one such technology that significantly reduces on-site manpower requirement and speed up construction. This paper outlines the pioneering & innovative PPVC technology of using a patented reinforced concrete composite structural wall system for construction of two 56-storey residential towers. Prototype sample tests such as compression test and shear tests had been carried out to verify the performance of this wall system; the test results show that this sandwiched combined wall system is able to perform under the actions of bending and shear in a composite manner satisfactorily. This development is currently the world's tallest residential building project constructed using the reinforced concrete modular construction technology.

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

1. Introduction.

The Avenue South Residence is a residential high-rise development at Silat Avenue in Singapore. 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.

To further enhance construction productivity, the Singapore Urban Redevelopment Authority (URA) encourages the building industry consultants and builders to adopt the Prefabricated Prefinished Volumetric Construction (PPVC) technology, which is an advanced and highly productive construction methodology that speeds up construction works significantly.

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 currently the tallest building project in the world adopting the reinforced concrete PPVC modular system when its last module was installed in January 2022. The previous height record was for 40 storey building [2, 3].

2. Architectural Constraints

As part of the planning design requirement, pocket sky gardens and a refuge floor (Fig. 1a & 1b) are required to be provided in the two towers as follows:

- 16 nos. of pocket gardens at different levels of the tower
- 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.

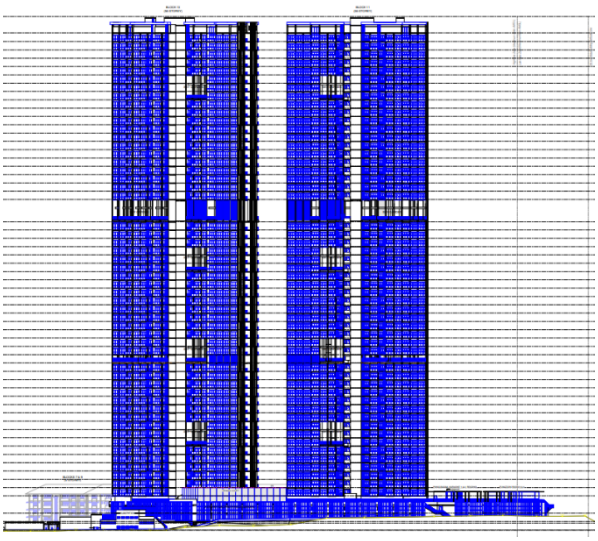

Fig. 1a. Pocket gardens and refuge floor

Fig. 1b. Close-up view of pocket gardens

3. Structural System

The super structure comprises mainly the two 56- storey high towers with two basements and two podium storeys of car park. The foundation system for the two towers and the podium comprises bored piles. The basement two slab is formed by pile raft whilst flat slab system is adopted for basement 1, 1st & 2nd storey. Beam slab system is adopted for 3rd storey.

The superstructure for the two tower blocks adopts the RC PPVC modular system for a minimum 65% of floor area in compliance with BCA's Code of Practice on Buildability, 2015 [4]. The remaining floor areas, which are mainly at the corridors, comprise conventional precast/in-situ RC beams and slabs linking the PPVC modules to the lift and staircase storey shelter cores. The corridor floor structures provide an effective connection to transfer lateral loads from the PPVC modules to the core walls.

4. PPVC System

4.1. PPVC Module – Weight Constraint

The weight of PPVC module is a major consideration in the transportation logistics and lifting operation. The module weight is designed to a minimum considering the tower crane lifting capacity & coverage. In particular, high strength concrete is used for the module walls to minimize its thickness according to design requirement.

4.2. PPVC Modularisation

Generally, the size and dimensions of the PPVC modules is controlled by the local transportation constraint and hoisting capacity of tower cranes.

In compliance with local road requirements & to avoid the need for auxiliary police escorts, the width of modules is to be contained within a 3.4m overall transport vehicle width (including load). The height of modules (including trailer bed) should also be considered if the transportation route involves passing below overhead bridges and gantries with height clearance of 4.5m.

Additionally, site access and loading/unloading areas need to be studied properly for the truck delivery, manoeuvrability, temporary storage on site and hoisting of the modules for the final installation.

To maximise productivity, ease of module prefabrication, site connectivity and installation, the PPVC module modularisation should take account of the following factors:

- Modules shape should be rectilinear as much as possible
- Module wall thicknesses should be uniform and standardized as much as possible
- The walls within each module should be aligned as much as possible

The **Avenue South Residence** used a total no. of 3034 of PPVC modules in the project

PPVC modularization plan for Tower 1 & 2 is shown in Fig. 2 below.

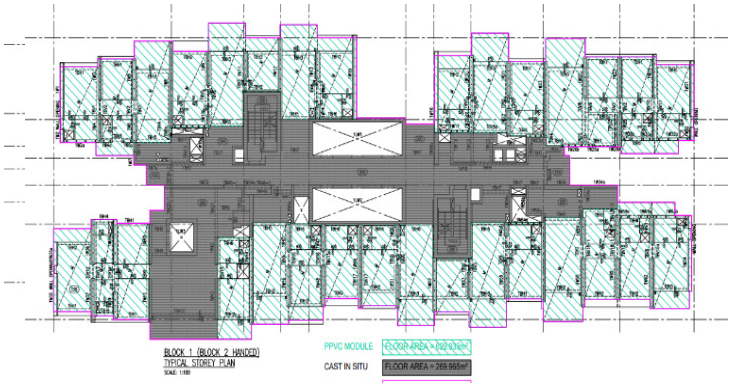

Fig. 2. Tower 1 & 2 PPVC Modularization Plan

4.3. PPVC Concrete Carcass Components

A typical PPVC concrete carcass (Fig. 3a & 3b) 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.

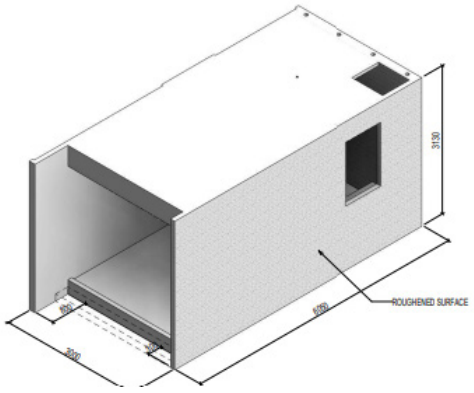

Fig.3a. Typical PPVC concrete carcass

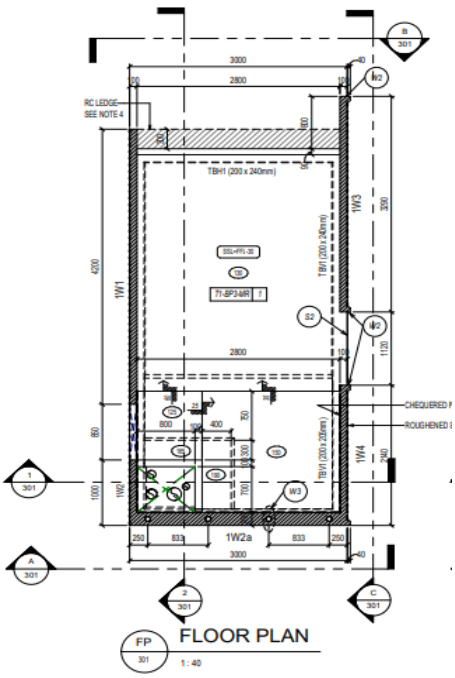

Fig. 3b. Typical PPVC module floor plan

4.4. Floor Slab

The RC floor slab spans across to the module walls is working as a horizontal diaphragm, transferring lateral loads to the lift and staircase shelters core walls.

4.5. Ceiling Slab

The ceiling slab is considered as a non-structural slab to provide rigidity to the module and help to brace the walls during transportation and installation; it also acts as a working platform during the module installation process.

4.6. RC Walls

Generally, the structural RC walls are located along the two long sides of the modules; designed to support the ceiling and floor slabs. Once installed, these walls are connected to adjacent module's walls via reinforcement embedded in self-levelling concrete within the joints to form a sandwiched composite structural wall. The sandwiched wall system is designed to behave in a composite manner under compression and bending actions. Thus, all the module walls are load-bearing and participate in the lateral load-resisting mechanism of the whole building.

4.7. 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.

5. Tower Lateral Load Performance

5.1. Wind Tunnel Test

Wind tunnel test 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.

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.

5.2. Lateral Analysis

ETABS [5] software has been used to model the performance of the tower blocks under lateral load. 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.

The performance of the towers under wind loads are shown in Table 1 & 2 below:

Table 1. 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 2. Mode shape – time period (s)

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

According to the analysis:

- 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

5.3. Tower Robustness

Tower block robustness has been checked under notional horizontal loads such that the blocks are capable of resisting a notional design ultimate horizontal load applied at each floor or roof level simultaneously equal to 1.5% of the characteristic dead weight of the structure between mid-height of the storey below and mid-height of the storey above in accordance with local design standards.

Structural ties, such as horizontal floor ties and vertical ties are provided and checked to comply with local design standards.

6. 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.

7. 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.

8. 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. The objective of the load tests was to verify whether the composite wall sample could withstand the design load in a composite manner.

9. PPVC Concrete Carcass Fabrication and Fit-Out Work

3-D fabrication method 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. 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 the Code of Practice on Buildability 2015 [2].

10. PPVC Installation on Site

Following module delivery to site, a heavy-duty tower crane with self-adjusting lifting frame was used to hoist the modules to their final position in installation. The main challenge during installation was the possible swaying of modules at height due to wind load. Experienced crane operator plays an important role in ensuring the PPVC module is lifted slowly and carefully so that the module is not tilting during hoisting and final positioning. The surface of the concrete slab receiving the modules has to be checked for levels; the platform receiving the module may be adjusted and levelled with shin plates where required. The modules would then be installed with reference to the surveyed gridlines marked on the receiving slab or top slab of the lower modules installed previously.

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. 14). 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.

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.

11. Buildable Design & Constructability Score

Based on local guidelines in BCA's Code of Practice on Buildability 2015 [2], 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. The photo of the completed towers is shown in Fig. 4

Fig.4. Photo of the completed towers

12. 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

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