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Case Study: The Use of Concrete Prefabricated Prefinished Volumetric Construction for Two Blocks of 40-Storey Residential Flats (The Clement Canopy) in Singapore

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Abstract: The Singapore Building Construction Authority (BCA) is transforming its built environment sector into one that is advanced in technology to raise the productivity. The Design for Manufacturing and Assembly (DfMA) approach has been identified as a key strategy to raise the productivity in the construction industry. This paper outlines the pioneering approach of using reinforced concrete sandwiched composite shear wall system as the Prefinished-Prefabricated-Volumetric-Construction (PPVC) technology in construction of two residential towers of 40-storey high in *The Clement Canopy* project in Singapore. The technology involves a LEGO-like construction method by joining the PPVC modules of the same floor side-by-side; followed by modules of the upper level stacking on top of the completed modules below and the cycle repeated until completion. The gaps in between the adjoining modules' walls were then filled with high-strength grout to connect them together such that the combined walls behave in a composite manner under loadings. Prototype tests had been carried out on the sandwiched wall panels with strain gauges installed to evaluate their behaviour under the actions of compression and bending. The test results showed that the sandwiched wall panels were able to withstand the loadings without delamination at the wall/grout interface, demonstrating that the designed sandwiched wall panel are able to behave in a composite manner under loadings. Installation of PPVC modules for the two towers was completed in approximately one year. The project achieved a manpower productivity data of 0.613 m^2/man-day, a marked improvement of 72% in productivity as compared to the Singapore Year 2017 Industry Average Project Productivity Data for Residential (non-landed) figure of 0.357 m^2/man-day. The project was successfully completed in Q1 of 2019 and is the tallest residential tower in the world at the time of project completion using the reinforced concrete PPVC technology. Advantages realised from the adoption of PPVC technology in this project includes improved productivity, early project completion; improved site safety, improved quality of end product and vast reduction in noise & dust pollution at the project site.

Keywords: Prefabricated Prefinished Volumetric Construction (PPVC), Reinforced Concrete Composite Shear Wall, Design for Manufacturing and Assembly (DfMA)

1. Introduction

The Clement Canopy is a high-rise residential development project by United Venture Development (Clementi) Pte Ltd, a joint venture between UOL Group Ltd and Singland Homes Pte Ltd. The project comprises two tower blocks of 40 storeys at Clementi Avenue One in Singapore. There are in total 505 residential units in the two tower blocks. The ancillary landscape, swimming pool and communal facilities are at the ground level. There is a multi-storey car park with one basement level linking the two towers.

To raise the construction productivity, the Singapore construction industry has been encouraged to embrace the Design for Manufacturing and Assembly (DfMA) [1] approach where significant portion of works are done off-site in a controlled factory-manufacturing environment. Prefabricated Prefinished Volumetric Construction (PPVC) is one such advanced and highly productive DfMA technology that speed up construction significantly. The PPVC modules are complete with internal finishes, fixtures and fittings in off-site factories, and are subsequently transported to job site for final installation.

The Clement Canopy project has adopted reinforced concrete PPVC system for the two residential towers according to the requirements as outlined in the Singapore Building Construction Authority (BCA)'s Code of Practice on Buildability 2015 [2].

With support from the Building Construction Authority (BCA) and working in tandem with the builder, TW-Asia Consultants Pte Ltd has pioneered the design and research of the reinforced concrete PPVC technology using Composite Shear Wall Structural System (European Patent EP3263795B). It was through such research, testing and continual development that this unique structural system was devised as one of the technical components for the PPVC methodology.

At the time of project completion, *The Clement Canopy* is the tallest building project in the world adopting the reinforced concrete PPVC system.

Figure 1. *View of the completed project.*

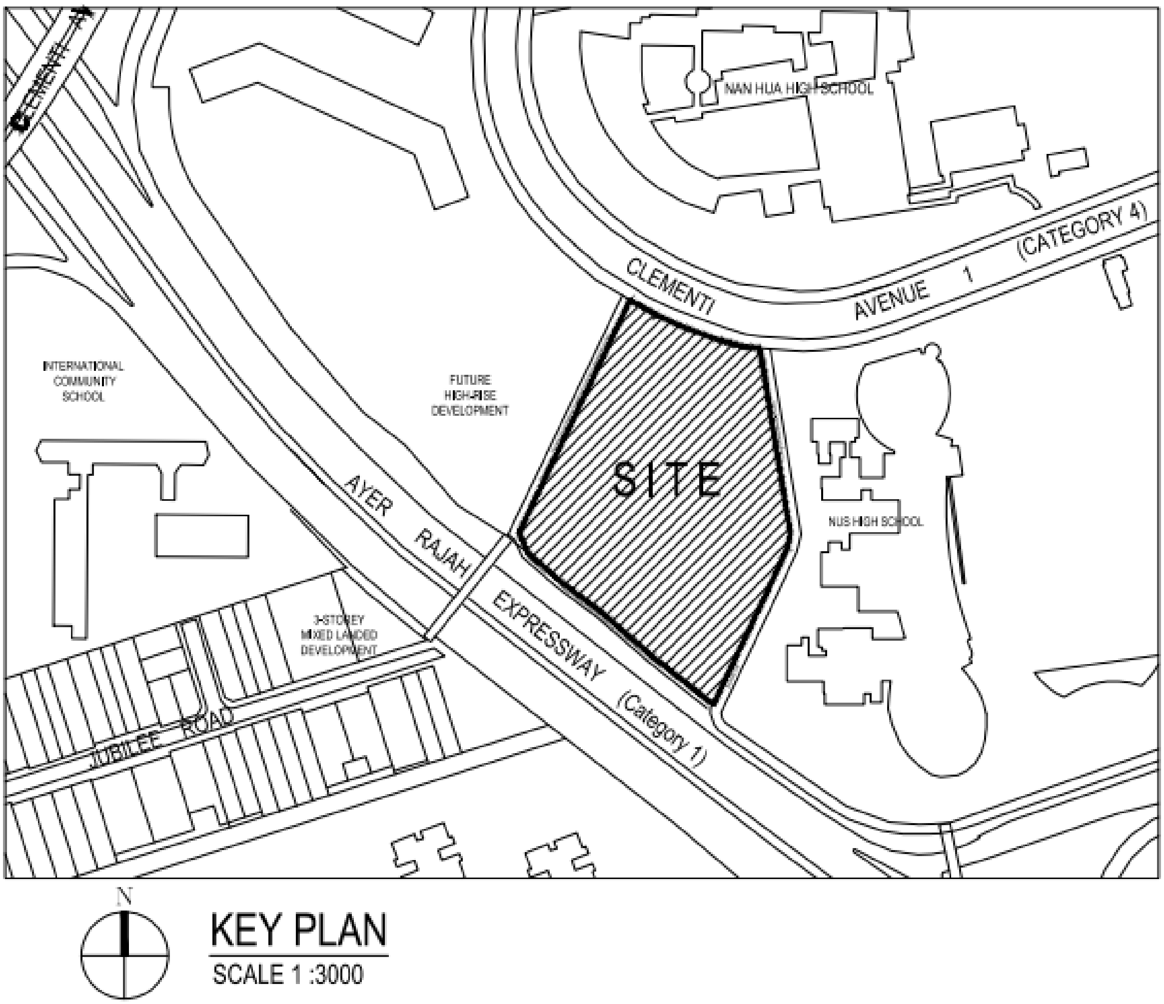

Figure 2. Location & site layout plan.

Some salient project data are as follows:

Table 1. *Project Data.*

Item	
Site Area	45,633 m^2
Proposed GFA (including bonus balcony & PES GFA)	50,196.3 m^2
Proposed Gross Plot Ratio (including bonus balcony & PES GFA):	3.85
Number of Tower Block	2
Total Number of Storey	40
Proposed Building Height AMSL	140 m
Typical Storey Height	3.15 m
Total Number of Residential Unit	505
Number of Residential Unit Type	8
Project Contract Period	36 months
Project Commencement Date	1 June 2016
Project TOP	Q1 2019

2. Structural System

While the PPVC technology is relatively new to the local construction industry, the core engineering design principles for structures including codes compliance that are adopted in conventional construction remains.

The main super structures comprise two 40-storey high towers and the podium five-storey multi-storey carpark. The foundation system for the tower blocks comprises bored pile whilst for the low-rise podium comprises jack-in spun piles.

The podium structures adopt a one-way full precast RC beam & slab system. The superstructure for the two tower blocks adopts RC PPVC system for minimum 65% of residential floor area in compliance with BCA's Code of Practice on Buildability 2015 [2]. The remaining tower floor areas, mainly at the lift lobby & corridor, comprise precast RC beam and slab linking the PPVC modules to the in-situ lift & staircase storey shelter cores. The lift lobby & corridor floor structures provide an effective linkage, transferring lateral loads from the PPVC modules to the strong core walls.

2.1. Design Codes

Design of the structures are based on and referenced to the relevant European Codes of Practice for loadings and concrete structures design [9-17]; the associated Singapore National Annex to the Eurocodes [18-26], and complying with the local building control regulations and guidelines [2-5, 7, 8]. Reference was also made to some international journals and publications [6, 27-30].

2.2. PPVC System - Modularization

The PPVC module size and dimensions are constrained by transportation vehicle size, width and height control of local roads and hoisting capacity of heavy lifting crane.

In compliance with the local Land Transport Authority's regulatory requirements, the PPVC modules are to be contained within an overall width of 3.4m (transport vehicle width including module) to avoid the necessity of engaging police escort. The module height including trailer bed should also be lower than 4.5m if the transportation route involves passing below overhead bridge and gantry.

In addition, the roads around the site, site access and holding areas need to be studied properly for the truck delivery, maneuverability, temporary storage and hoisting of the modules.

For ease of modules off-site prefabrication, handling, lifting, on-site jointing & installation, as much as possible, the modules should be rectilinear in shape, walls' thickness should be uniform, standardized and aligned within the module.

Breakdown of PPVC modules in this project can be summarized as follows:

Table 2. *PPVC Modules Breakdown.*

Item	
Total no. of Modules	1866
No. of Modules in Tower 1	862
No. of Modules in Tower 2	1004
Number of Tower Block	2
Largest Module (width x length x height	3.1m x 8.35m x 3.15m
Smallest Module (width x length x height	3.0m x 5.75m x 3.15m
Maximum Module Width	3.1m
Height of Module	3.15m
Weight of Module	14 to 29 ton

Tower 1 modularization plan is as shown below:

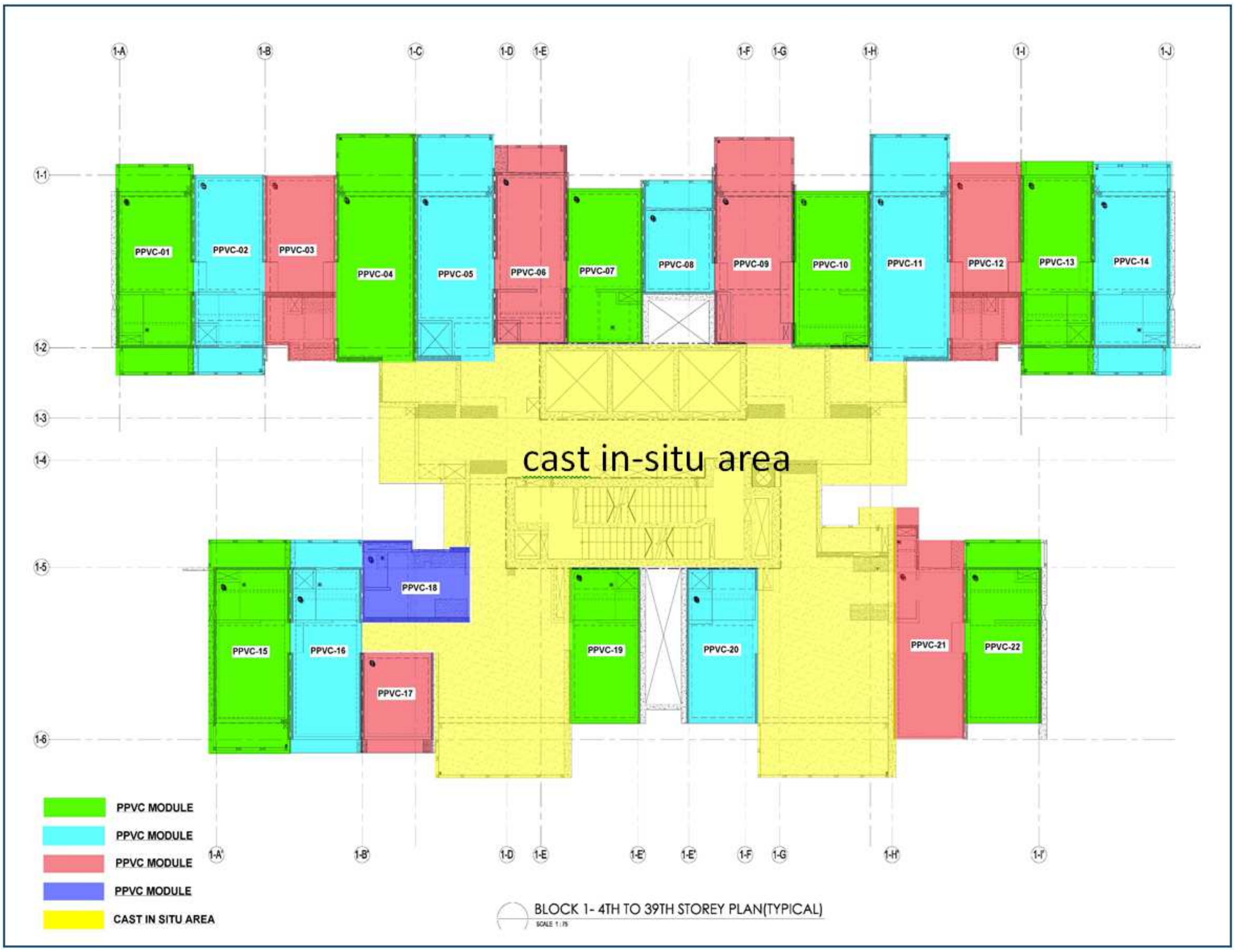

Figure 3. Tower 1 modularization plan.

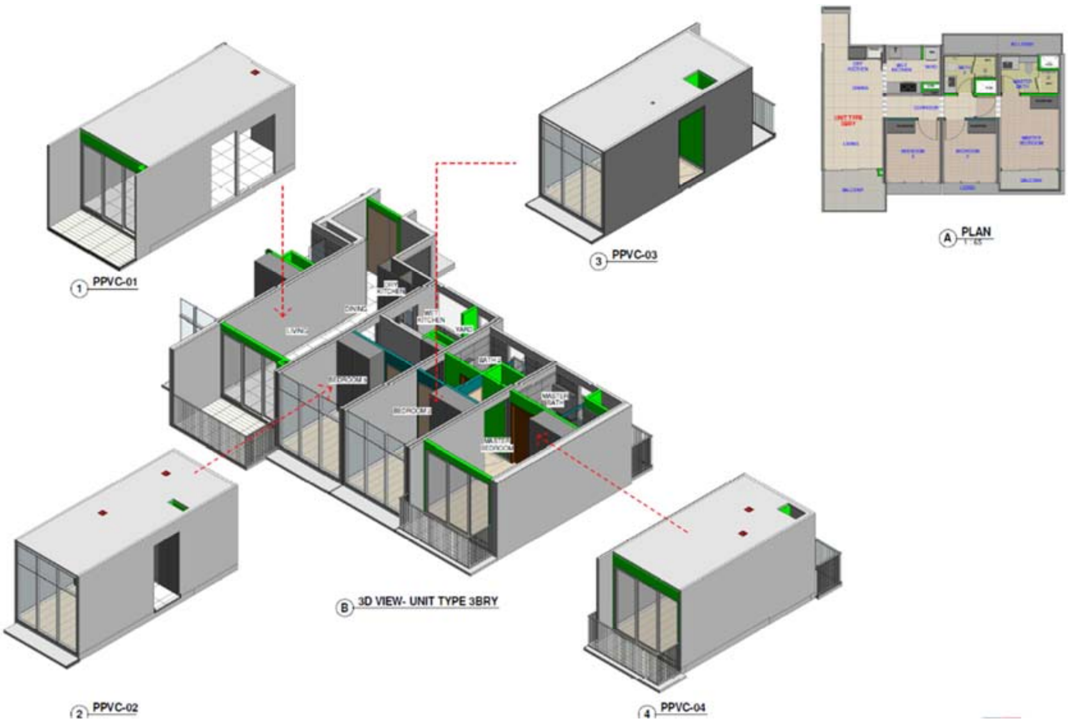

Figure 4. Modules for a typical residential unit.

2.3. PPVC Concrete Carcass

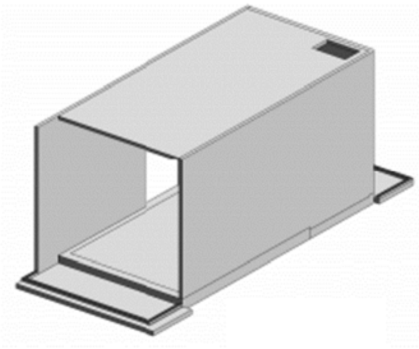

Figure 5. *Typical PPVC concrete carcass.*

A typical PPVC concrete carcass includes a floor slab, a ceiling slab, two side structural walls, and non-structural end wall/s which may incorporate a door or window opening.

The floor slab spans across the module side walls and also works as a horizontal diaphragm, transferring lateral loads to the staircase shelter and lift core walls.

The ceiling slab is supported on the perimeter walls or beams. Besides bracing the walls during transportation and installation, it also supports ceiling finishes/fixtures and acts as a working platform during module installation on site.

The structural walls are located along the two long sides of the modules; supporting the top ceiling and bottom floor slabs.

With a floor height of 3.15m in this project, the PPVC module system is able to achieve an internal clear height of 2.79m.

2.4. PPVC Module Connection

The structural walls of a typical module are joined to the walls of adjacent modules with reinforcement & high-strength grout to form a sandwiched wall. This sandwiched wall system is designed as load-bearing in a composite manner and participates in the lateral load-resisting mechanism of the building.

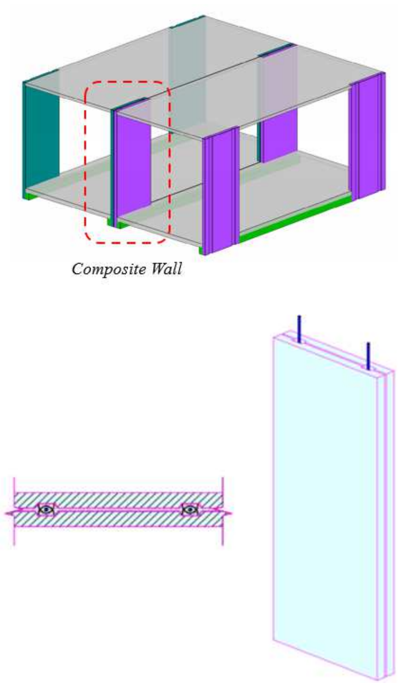

Figure 6. *Composite wall system.*

The adjacent modules are joined together with provision of structural ties in both vertical and horizontal directions in accordance with the design code requirement. The modules are further connected to the in-situ structures with reinforcement bars with adequate anchorage or lapping length. With this structural connectivity, the horizontal diaphragm action is ensured in transferring lateral loads to the in-situ lift/storey shelter core wall structures.

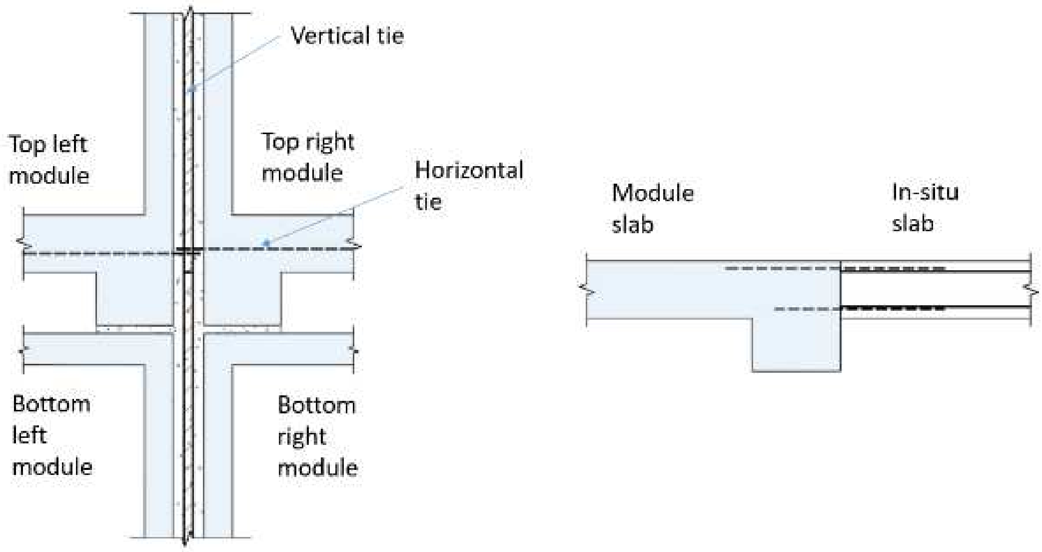

Figure 7. *Typical module connection.*

2.5. Tower Lateral Load Performance

Commercial software, ETABS was used to model the tower block performance under lateral load. The building top displacement and inter-storey drift ratio are controlled to be less than 1/500.

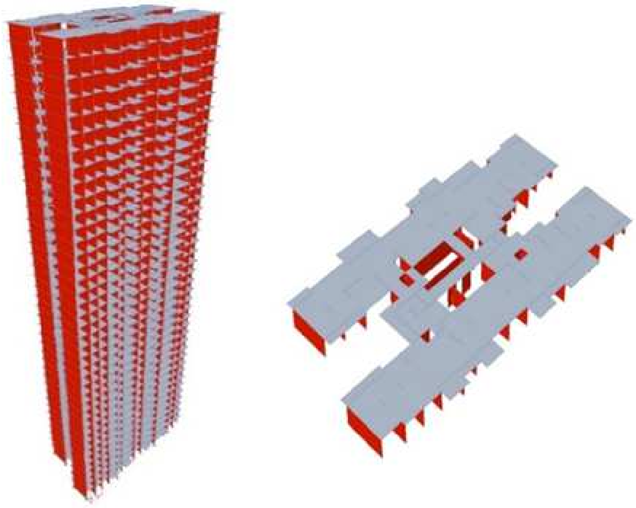

Figure 8. *Etabs 3D model.*

The performance of the towers under lateral loads are as follows:

Table 3. *Tower lateral displacement under wind load.*

Displacement	Tower 1	Tower 2
Building top displacement ratio, Δ/H	1/1235	1/1178
Inter-storey drift ratio, δ/h	1/965	1/909

Table 4. *Mode shape & period(s).*

Mode	Tower 1	Tower 2
1 (X-Translational)	4.74	4.92
2 (Y-Translational)	3.95	4.06
3 (Torsional)	3.51	3.05

2.6. Tower Robustness

In addition to wind loads, the tower blocks were also checked for robustness under notional 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 either mid-height of the storey above or the roof surface in accordance with local requirement as per CP 65: Part 1: 1999 Structural Use of Concrete [8].

Structural ties such as horizontal floor ties & vertical ties were checked to comply with the provisions in SS EN 1992-1-1: 2008 [13] & the corresponding Singapore National Annex.

2.7. Durability and Fire Resistance

The structures have been designed to Structural Class S4 (Design working life of 50-year) with Exposure Class XC3 (Corrosion induced by carbonation - moderate humidity) to SS EN SS EN 1992-1-1: 2008 [13] & the corresponding Singapore National Annex. The structures are designed for a fire resistance of 1.5 hours in accordance with local requirement. Fire compartmentalization is achieved by separation of floors by the floor slabs; separation of vertical compartments by RC wall or rated partition.

3. PPVC Wall Prototype Load Tests

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

3.1. Compression Test

The objective of the prototype test was to verify whether the sandwiched composite wall could withstand the design compression load in a composite manner. Strain gauges were installed across the wall/grout interface to check whether delamination would occur under test loading. Test sample size of 1m x 3m x 0.2m (length x height x thickness) was adopted in the test. The sample was loaded up to two times the design working load using prestressing bars; the sample was able to withstand the final test load without failure. There was no delamination observed at the wall/grout interface, demonstrating that the sandwiched wall sample was able to behave in a composite manner under compression load.

Figure 9. *Compression test set-up.*

3.2. Bending Test

Similar to the Compression Test, the objective of the prototype bending test was to verify whether the sandwiched composite wall would behave in a composite manner under bending action. Strain gauges were installed at the wall/grout interface to verify whether delamination would occur during loading. The test sample of size 1m x 3m x 0.2m (width x length x thickness) was used. The sample was jacked at mid-span using hydraulic jacks until flexural cracks formed at the tensile face of the sample. There was no delamination observed at the wall/grout interface; the test shows that the sandwiched wall panel had performed satisfactorily under bending in a composite manner.

Figure 10. *Bending test set-up.*

4. PPVC Module Fabrication

4.1. PPVC Concrete Carcass Fabrication

The PPVC concrete module carcass was manufactured in a precast factory in Johor, Malaysia. The module carcass fabrication adopted a 2D method where the module walls were fabricated first; this was then followed by casting the floor & ceiling slabs and joined to the completed wall panels to form the final 3D module. M&E services to be embedded in the wall panels and slabs were coordinated accurately before casting. Structural ponding test was carried out to check for water-tightness of the completed floor slab and at the wall/slab joints.

The concrete surface of the wall panels was roughened to washed aggregate finish. This was to ensure good bonding between the precast wall panels and the in-situ grouting on site.

The following activities at the precast factory were particularly critical in ensuring good quality control:

1. Checking accuracy of module dimensions, verticality & levels to be within tolerances to ensure smooth installation on site;
2. Checking steel mould dimensions, rigidity and stability to ensure accuracy of finished concrete carcass dimensions. Checking of steel mould shall be done after mould assembly and after demoulding;
3. M&E services embedded in carcass shall be coordinated properly & accurately with the adjacent modules for smooth connection on site.

Figure 11. *Fabrication of wall panel.*

Figure 12. *Fabrication of slab.*

Figure 13. *Completed PPVC concrete carcass.*

4.2. PPVC Fit-out Works

The completed module carcasses from Malaysia were delivered to a fit-out factory in Singapore for further Architecture finishing & M&E fit-out works. Water-proofing works and ponding test were also carried out in the fit-out factory to ensure water-tightness at the wet areas.

The level of finishing and fittings to be completed in the fit-out factory shall be in accordance with the local Code of Practice on Buildability 2015 [2] as follows:

Table 5. *Minimum level of completion off-site.*

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

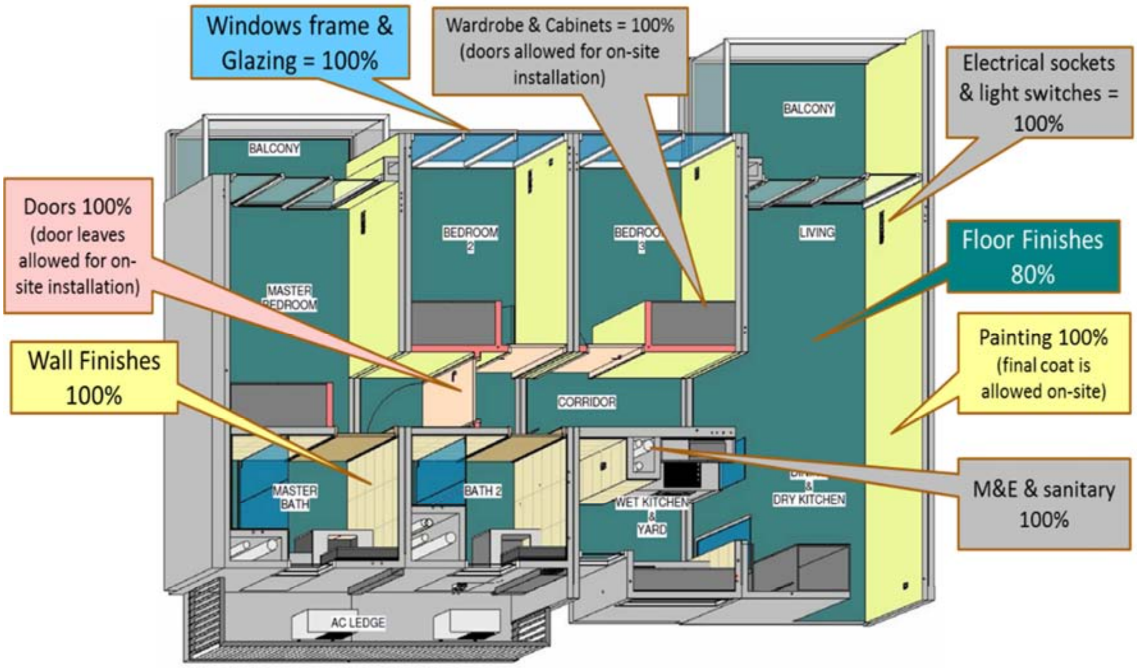

Figure 14. *Minimum level of completion off-site (graphical).*

Figure 15. *Finishing & fitting works in progress.*

In the fit-out factory, the modules for each residential unit were arranged and trial fitted. Module dimensions, verticality & levels were double checked for correctness. This was to ensure that the adjoining modules could match each other well before delivery to site for final installation. The modules were also provided with proper labelling for easy identification during site installation.

4.3. PPVC Installation on Site

At the site, the PPVC modules were lifted by a heavy-duty tower crane with a lifting frame which helped in distributing the load evenly. The centre of gravity of the lifting frame and the module should be concentric so that the module is not tilting during hoisting to facilitate final positioning and installation.

Tower crane has to be positioned at strategic location considering the reach and weight of the modules. Logistic space of delivery, access, unloading and temporary site storage must also be considered to ensure smooth installation.

Figure 16. *Trial fitting of modules for a residential unit.*

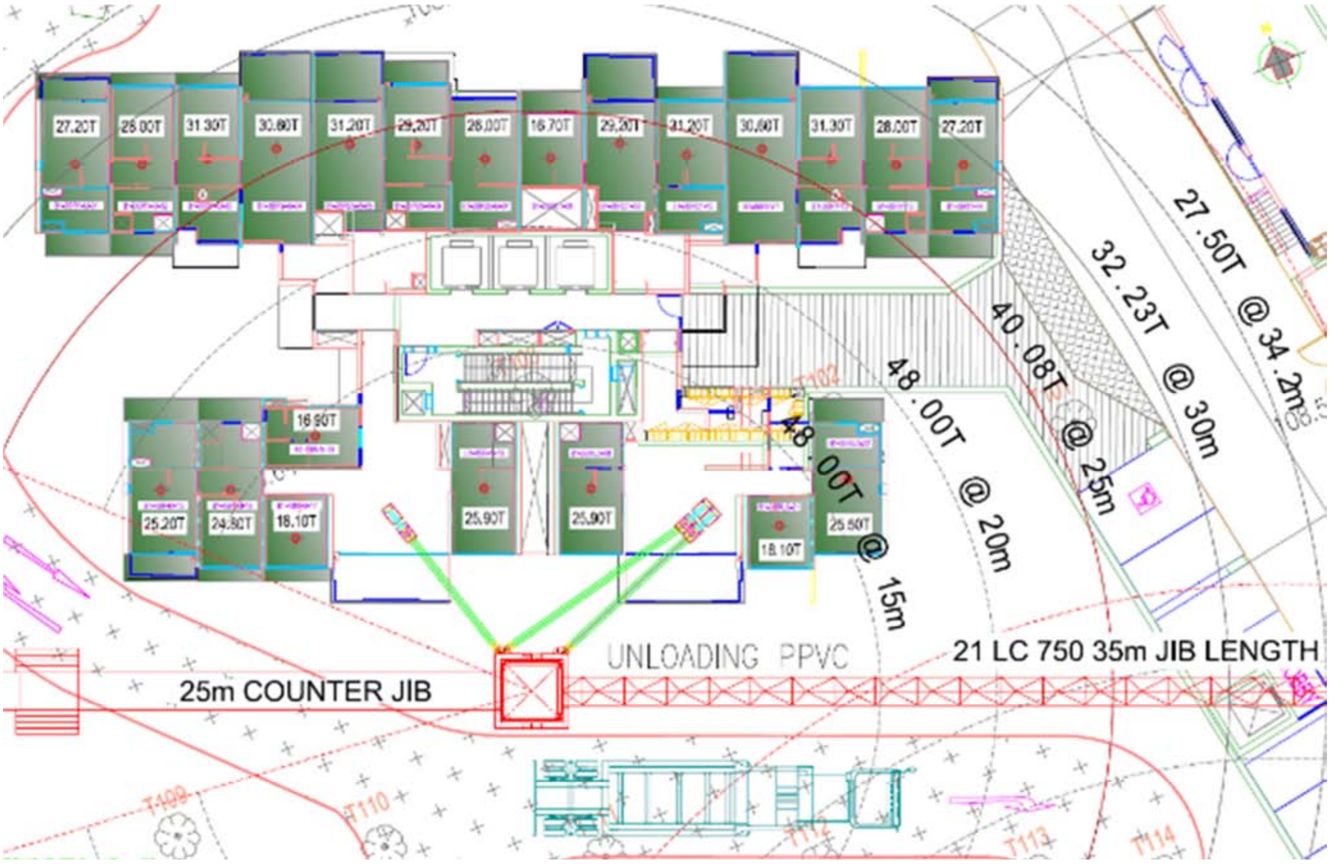

Figure 17. *Tower crane positioning.*

Figure 18. *Hosting of module.*

Surface of the concrete slab receiving the first layer of modules has to be levelled, position of walls surveyed & marked and alignment pins provided to aid in the positioning & installation of modules. Installation of modules has to be planned properly in a sequential order both horizontally and vertically.

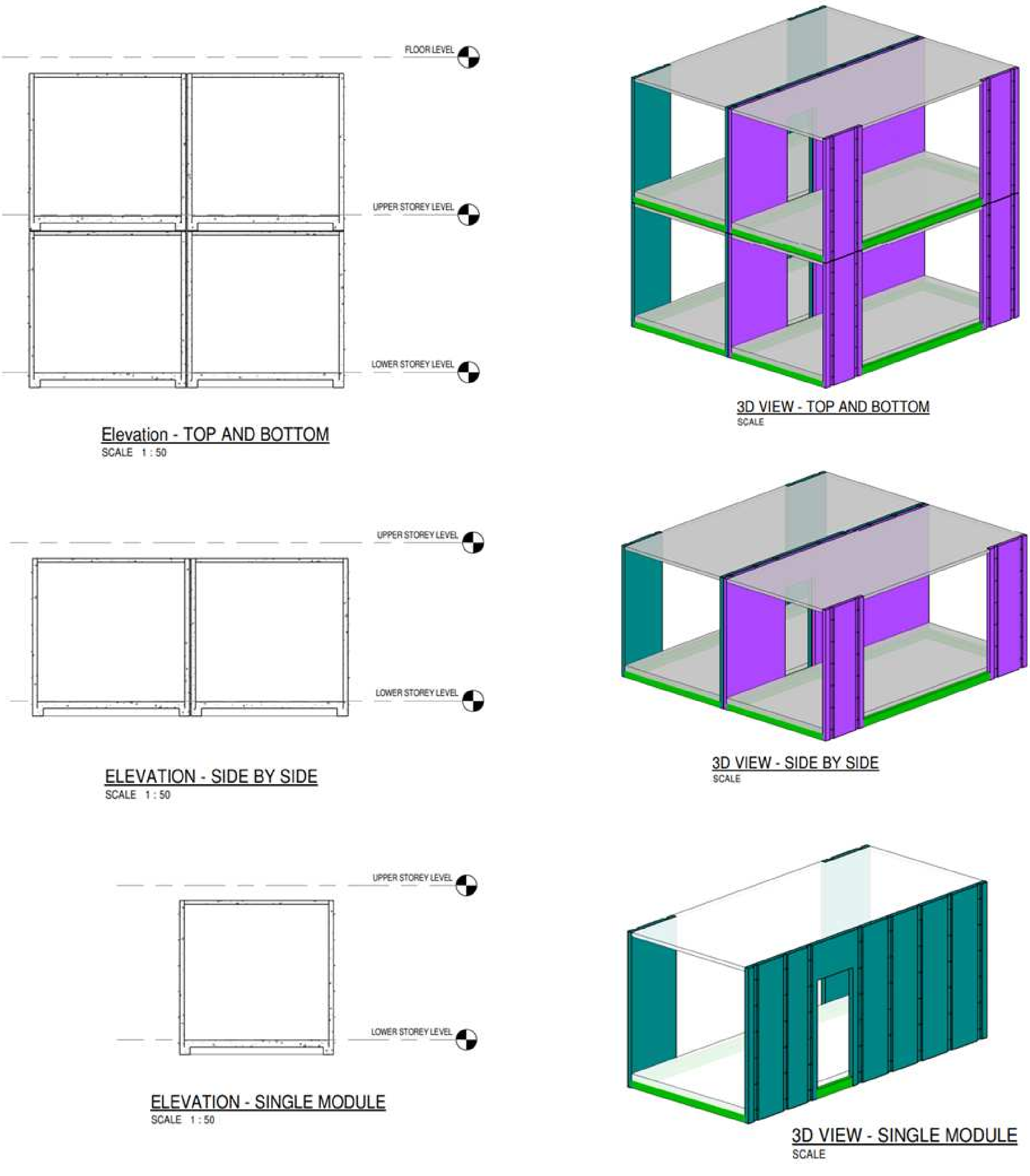

Figure 19. *Installation & stacking of modules.*

Alignment guide pins were provided at corners of modules to facilitate installation of the modules. Backer rods and grout stopper were provided to prevent grout loss during in-situ grouting of the joints. Upon installation, the gaps between walls of the adjoining modules were grouted with high-strength grout.

M&E Services in a typical PPVC module generally comprises vertical stacks which are used for sanitary pipes; water distribution pipes crossing between modules and electrical cables crossing between modules and etc. The M&E services between adjoining modules were finally connected; light fittings, equipment & fixtures were then installed. The final Architectural floor finishes, painting, door leaves, wardrobe, cabinet doors were also installed during this stage.

External surface of the modules' joints was provided with water-seepage control measures comprises layer of fibre mesh and cementitious water-proofing membrane.

5. Productivity

5.1. Buildable Design & Constructability Score

Based on local BCA's Code of Practice on Buildability 2015 [2], by adopting the PPVC technology, this project has achieved marked improvement in the Buildability and Constructability Score. Total Buildable Design Score calculation achieved is 95, which is higher than the minimum required Buildable Score of 88; total Constructability Score for this project is 67, which is higher than minimum required Constructability Score of 60.

5.2. Manpower Productivity

By using the PPVC technology, this project has managed to achieve a manpower productivity data of 0.613 m^2/man-day. Compared with the Singapore Year 2017 Industry Average Project Productivity Data for Residential (non-landed) figure of 0.357 m^2/man-day, this project has achieved a 72% improvement in productivity.

The total duration of module installation in this project is approximately 12 months; the average floor cycle is 6 to 9 days. As expected, the first 2 to 3 floors took longer cycle time as they were in the initial learning curve of module installation.

Figure 20. *Commencement of module installation (April 2017).*

Figure 21. *Completion of module installation (April 2018).*

6. PPVC Challenges

For a project to adopt PPVC technology successfully, the following challenges need to be considered in the early planning stage to ensure a smooth supply chain of modules from off-site fabrication to final installation on site:

1. *Mindset changing and close collaboration* – Client, consultants, builder and project team members must have a common mindset, understanding and close collaboration in the adoption of PPVC technology, which is different from conventional construction methodology.
2. *Early contractor involvement* – Engage contractor with knowledge of PPVC technology.
3. *Early plan layout design* – Early confirmation of Architecture layout plan complying with Client's requirements.
4. *Module size constraint* – Early planning of module size considering transportation trailer size and road transportation route constraints.
5. *Heavy-duty tower crane lifting* – Sourcing for heavy-duty crane locally or overseas.
6. *Module weight constraint* – Control module weight to be within the crane lifting capacity.
7. *Fitting-out factory space* – Sourcing for big factory space & facility for module finishing & fit-out works.

8. *Module Temporary Holding Area on Site* - Ensure sufficient space for site access, maneuverability, holding area for 'Just in time' approach for lifting & installation.
9. *Façade design*- Avoid pattern groove lines that require vertical or horizontal groove line alignment.

7. Conclusions

This project has successfully adopted the RC Composite Wall System as the PPVC technology in the construction of the two 40-storey residential towers in Singapore.

The adoption of PPVC system in this project has achieved marked improvement in Buildability Score, Constructability Score and manpower productivity.

Advantages realised from the adoption of PPVC system in this project includes improved productivity, early project completion; improved site safety as on-site activities are reduced tremendously; improved quality of end product as most activities are done in a factory-controlled environment and vast reduction in noise & dust pollution at the project site.

One of the main challenges of reinforced concrete PPVC system is the huge module weight which require heavy-duty lifting crane. Future improvement to the RC PPVC system may involve reducing the module weight by using light-weight concrete floor, high-strength concrete and steel-concrete composite section for the walls.

Where space permits, it would be ideal if the fabrication of the module carcass and finishing fit-out works can be housed in a single-location factory to reduce the logistics costs.

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