# Building the Future with **Prefabrication Volumetric Module**

## Productivity and Jointing System

CIDB Technical Publication No.: 2111

CIDB MALAYSIA

Building the Future with
# Prefabrication Volumetric Module

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**CONSTRUCTION INDUSTRY DEVELOPMENT BOARD MALAYSIA (CIDB)**
10th Floor, Menara Dato' Onn,
World Trade Centre,
No. 45, Jalan Tun Ismail,
50480 Kuala Lumpur,
MALAYSIA



# PREFACE

Throughout the history of the construction industry, great strides and advancements have been reached by its undergoing a significant paradigm shift. Now, the industry is observing a growing trend towards multi-trade prefabrication. It is believed that this practice will continue to grow in coming years to focus on approaches that support and propel the industry forward.

Another growing trend is off-site construction applying three-dimensional (3D) volumetric modules, also known as Prefabricated Prefinished Volumetric Construction/ Volumetric Modular Construction, using Prefabricated Volumetric Module (PVM). PVM construction involves the prefabrication of whole building units under controlled conditions in factories. These units are then transported to the construction site, where they are installed and assembled on-site to create functional buildings. According to latest definition of prefabricated IBS by Mohd Zairul, (2021) as an innovative process of building components utilising mass production Industrialised systems, produced within a controlled environment (on or off-site) which includes organised logistics and installation process on-site with systematic planning and management.

This present document titled "**Building the Future with Prefabrication Volumetric Module - Productivity and Jointing System**" produced by the Construction Industry Development Board (CIDB) Malaysia via the Construction Research Institute of Malaysia (CREAM) will be used as a primary reference to provide information about the productivity level of building construction projects using PVM, and PVM connection and jointing systems available in general.

The CIDB wishes to express their gratitude and appreciation to the IBS manufacturers, contractors, consultants, developers, and all industry players involved in sharing data, experiences, and knowledge towards the success of this report's development. This document will be a useful reference for policy-makers to encourage the construction industry players to be game-changers for the betterment of the industry in moving towards Construction 4.0. Furthermore, it will help to cultivate increased productivity performance, high-quality building construction, improve on-site safety, minimise environmental impacts, and accomplish economy of scale in IBS production.

# Building the Future with Prefabrication Volumetric Module

# EDITORIAL

This research was funded by the Construction Industry Development Board (CIDB) Malaysia and executed by the Construction Research Institute of Malaysia (CREAM). We would like to thank the editorial team for their contribution and support.

# ABBREVIATIONS

| | |
|---|---|
| CFT | Concrete-filled tube |
| CIDB | Construction Industry Development Board |
| CLQ | Centralized Labour Quarter |
| CREAM | Construction Research Institute of Malaysia |
| GFA | Gross Floor Area |
| HSS | Hollow steel section |
| IBS | Industrialised building system |
| MEP | Mechanical, Electrical & Plumbing |
| MMC | Modern Method Construction |
| MSB | Modular Steel Building |
| OSM | Off-site Manufacturing |
| PPVC | Prefabricated Prefinished Volumetric Construction |
| PVM | Prefabricated Volumetric Module |
| RC | Reinforced Concrete |
| SQFT | Square Foot |
| SQM | Square Metre |

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Productivity and Jointing System

# 1.0 INTRODUCTION

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Prefabrication Volumetric Module (PVM) is a typical construction method in developed countries such as the United Kingdom, the United States of America, Australia, Japan, and many others. This construction method has currently become a growing trend in the Malaysian construction industry. PVM is also known as Volumetric Modular Construction/ Modular Construction, Off-site Manufacturing (OSM)/ Off-site Construction, Modern Method Construction (MMC), Prefabricated Prefinished Volumetric Construction (PPVC), Modular Integrated Construction and Prefabricated Modular. Table 1.1 shows the world's tallest PVM buildings and their respective number of storeys.

Table 1.1: World's Tallest PVM Building (Thai, Ngo, & Uy, 2020)

| Project | Storeys | Year | Country | Modular type | Material | Highlight |
|---|---|---|---|---|---|---|
| Collins House | 60 | 2019 | Australia | 2D Panel and 3D Module | Concrete | The tallest building combining both penalised and PVM method |
| J57 Mini Sky City Tower | 57 | 2015 | China | 2D Panel | Steel | The fastest-built building upon completion (in 19 days) |
| Croydon Tower | 44 | 2020 | United Kingdom | 3D Module | Steel | The tallest PVM building upon completion |
| Atira Student Accommodation | 44 | 2018 | Australia | 2D Panel and 3D Module | Concrete | Combined of both penalised and PVM methods |
| La Trobe Tower | 44 | 2016 | Australia | 2D Panel and 3D Module | Concrete | Combined of both penalised and PVM methods |
| Clement Canopy | 40 | 2019 | Singapore | 3D Module | Concrete | The tallest PVM building |
| B2 Tower | 32 | 2016 | United State | 3D Module | Steel | The tallest PVM building upon completion |
| T30 Tower | 30 | 2011 | China | 2D Panel | Steel | The fastest-built building upon completion (in 15 days) |
| Apex Tower | 29 | 2017 | United Kingdom | 3D Module | Steel | The tallest PVM building in Europe |
| SOHO Tower | 29 | 2014 | Australia | 3D Module | Steel | The tallest PVM building upon completion |

## 1.1 Benefits and Challenges of PVM Construction

### *1.1.1 Benefits of using PVM Construction*

According to Abd Hamid, Mat Kilau, Mohd Zain, & Musa, (2019); CIDB Malaysia, (2019 & 2020a), PVM offers advantages such as improved build time, environmental benefits, and reduced on-site labour cost as shown in **Figure 1.1.** It also incorporates a broad range of technologies and innovations to improve project delivery.

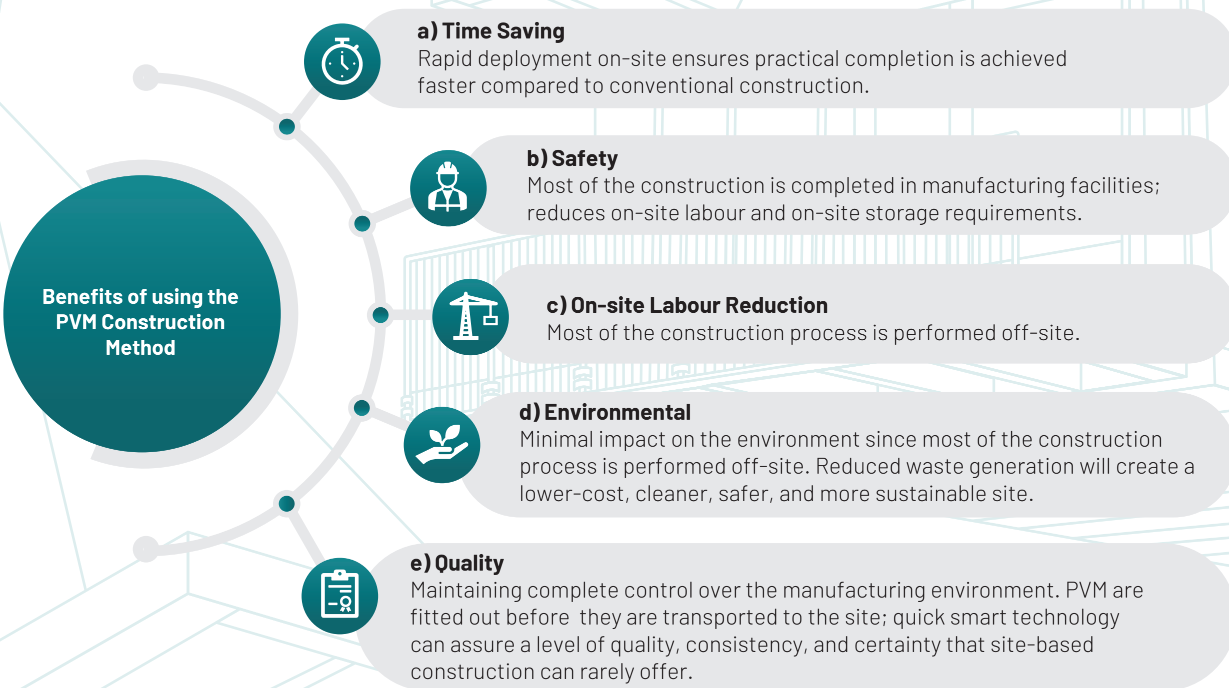



Figure 1.1: Benefits of using the PVM Construction Method

### *1.1.2 Challenges in using PVM Construction*

Despite the many benefits of using the PVM construction method, Figure 1.2 highlights five expected challenges that are commonly faced by the construction industry, which were derived from numerous surveys and literature from previous researchers (Kamali & Hewage, 2016; Lacey, Chen, Hao, & Bi, 2018; Razkenari, Fenner, Shojaei, Hakim, & Kibert, 2020).

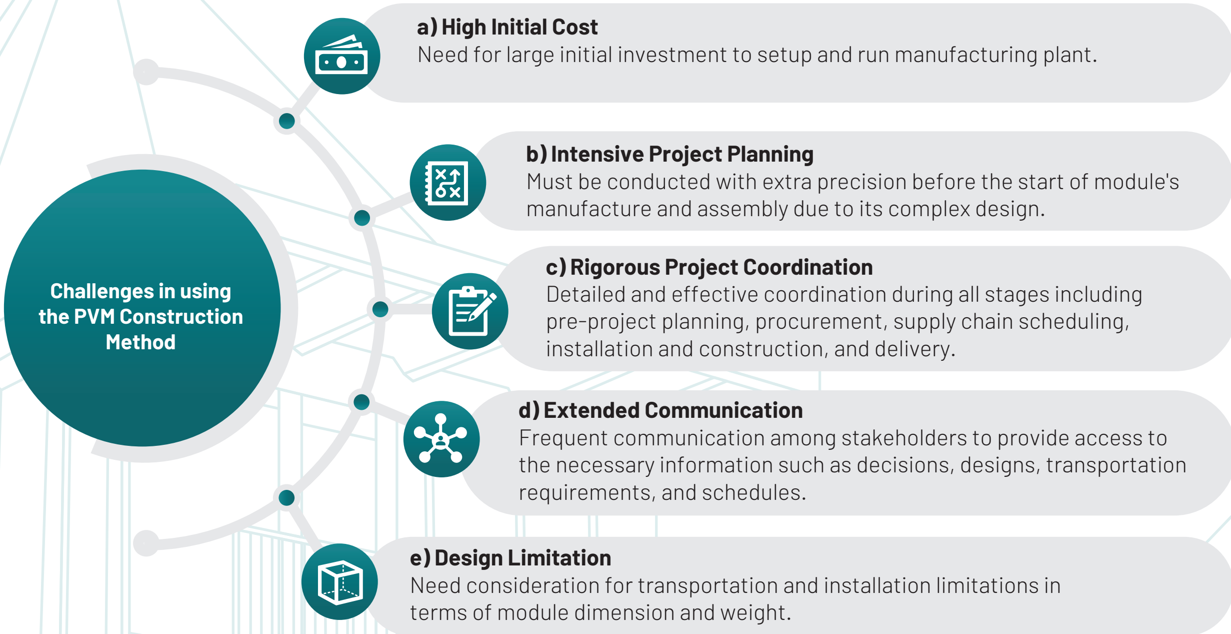



Figure 1.2: Challenges in using the PVM Construction Method

## 1.2 PVM Classification

PVM can be classified according to: 1) primary construction material; 2) load transfer mechanisms; and 3) structural systems.

### *1.2.1 PVM Classification Using Primary Construction Material*

According to Lacey et al. (2018), PVM can be classified according to the primary construction material such as concrete, metal, or timber as shown in **Figure 1.3** to **Figure 1.5**. For metal PVM, it can be further classified as Modular Steel Building (MSB), light steel-framed modules, and shipping container modules. **Table 1.2** shows the applications, advantages, and disadvantages of each PVM classification.

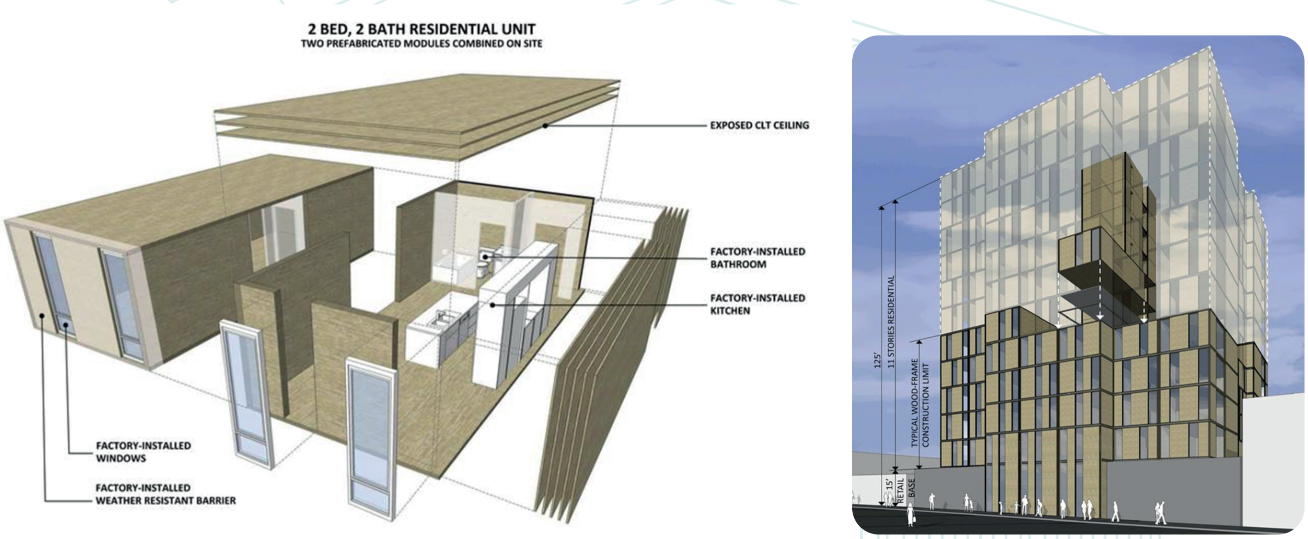
*Sources: Aurélie Cléraux (2018)*

Figure 1.3: Example of Precast Concrete PVM

*a) MSB Module* *b) Light Steel Framed Module* *c) Shipping Container Module*

*Sources: Lacey et al. (2018)*

Figure 1.4. Example of Metal PVM




*Sources: Alter (2014)*

Figure 1.5. Example of Timber PVM

Table 1.2: PVM Primary Material Classification

| PVM Type | Application | Advantages | Disadvantages |
|---|---|---|---|
| **a) Metal PVM** | | | |
| • MSB Module | Hotels, residential apartments | Suitable for high-rise buildings, high strength | Corrosion, lack of design guidance |
| • Light Steel Framed Module | Maximum 10-storey, 25-storey with additional core | Lightweight, easy to transport and install | Suitable mainly for low-rise buildings |
| • Shipping Container Module | Post-disaster housing, military operations, workers' quarters, and residential development | Recyclable shipping containers, easy to transport | Additional reinforcing required to strengthen the container when openings are cut in the walls |
| **b) Precast Concrete PVM** | Hotels, prisons, residential apartments, educational buildings, etc. | Fire resistant, acoustic insulation, thermal performance, high capacity | Heavy to transport and install, potential cracking at corners |
| **c) Timber Frame Module** | 1 to 2-storey high buildings, educational buildings, housing | Sustainable material, easy to assemble, easy to transport and install | Poor fire resistance, need extra treatment to improve durability |

*Adapted from Lacey et al. (2018)*

### *1.2.2 PVM Classification Using Load Path*

According to R. M. Lawson, Ogden, & Bergin, (2012) and Liew, Chua, & Dai (2019a), there are two common types of PVM systems with different types of load paths:

1. load-bearing wall modules, and
2. corner-supported modules.

Load-bearing wall modules are commonly used in concrete buildings, in which the concrete walls are used to transfer gravity loads to the foundation, as well as resisting the lateral loads as illustrated in **Figure 1.6.** Meanwhile, corner-supported modules are generally made of steel, in which the gravity loads are transferred to the slab, then to the edge beams and corner columns, and finally to the foundations as shown in **Figure 1.7.** In this system, separately braced frames or reinforced concrete core walls resist the lateral load.

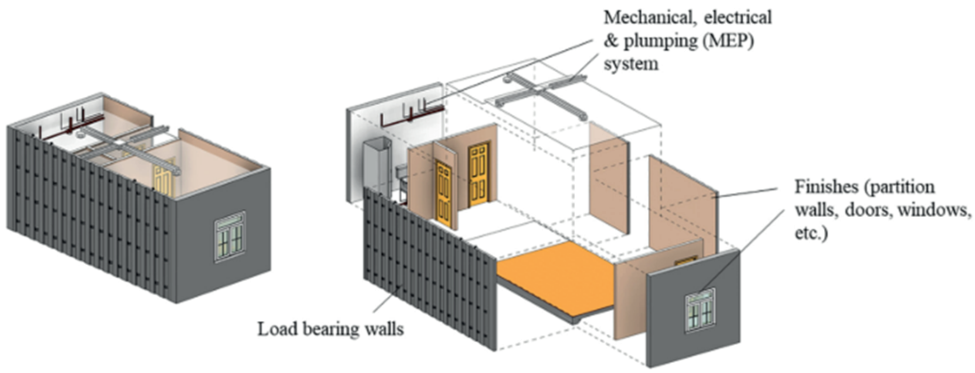



Figure 1.6: Load-bearing PVM System (Liew et al., 2019)

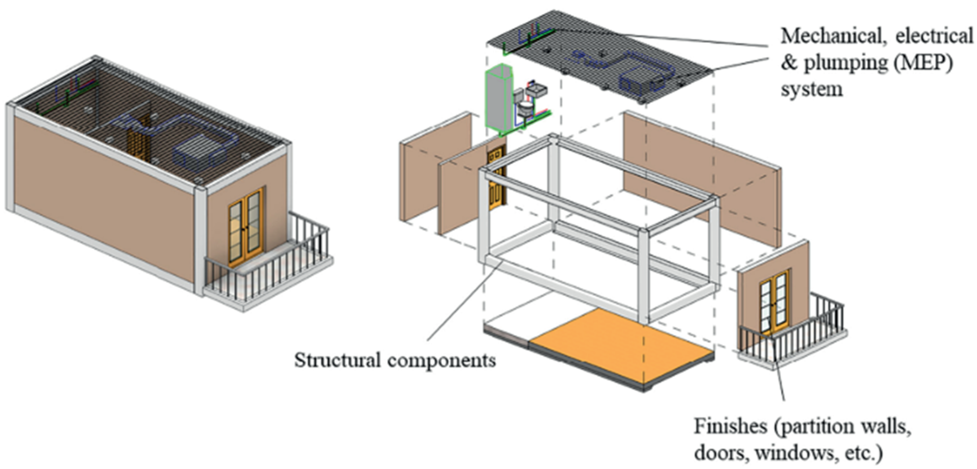



Figure 1.7: Corner-Supported PVM System (Liew et al., 2019)

### *1.2.3 PVM Classification Using Structural System*

According to Gunawardena (2016), existing PVM buildings can also be categorised according to the structural system that has been used as follows:

1. **Load-Bearing System**

   The gravity loads of each stack of modules are run down through the side walls down to the foundation. The neighbouring modules do not share loads or transfer any lateral loads from one to the other. This load-bearing system is the same as the load-bearing wall module under load path classification.

2. **System with Central RC Core and modules that are directly connected to the core**

   Here, the system consists mainly of corner-supported modules as previously introduced previously PVM load path classification. The gravity loads are directly transferred down to the foundation through the perimeter or corner columns of each module. One vertical stack of modules acts as one block of vertical loads. This system can go up to any height, and typically result in structures of 8 to 10 storeys high. The lateral load-resisting system is essentially managed by the central core that is made out of reinforced concrete. The modules are connected laterally to the central core either directly or through neighbouring modules. The lateral loads are expected to be transferred to the foundation mainly through the central core.

3. System with Central RC core where modules are stacked up in rows and the floor levels are eventually poured with concrete

The poured concrete fills up the vertical gap between the roofs of a certain level of modules and the floors of the level of modules directly above it. Once hardened, this concrete membrane acts as a rigid diaphragm that is continuous and connected to the core, and can transfer all of the lateral loads to the core. However, this results in excessive use of the material in the form of concrete, where the floors and roofs of each module are already in place. It also hinders the ability of the modules to be removed and reused in a different location. In practice, this system has been used in buildings that go up to 25 to 30 storeys high.

4. Advanced Corner-Supported Modular System with stiff modules

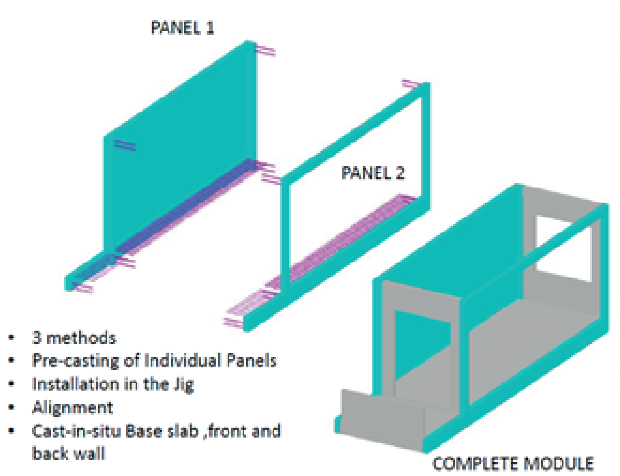
This is a system where the dependency of the central core is no longer a constraint to the structural system. This system is self-sustained as far as the lateral load resistance is concerned. The modules themselves are allowed to incorporate stiff wall elements, and are placed strategically on a building plan to ensure effective lateral load resistance. The system presents designers with many attractive benefits, including flexibility with arranging spaces without being restricted by an in-situ unmovable core. This prompts the need for this structural system to be investigated further on its structural behaviour against lateral loads to be used for medium to high rise structures.

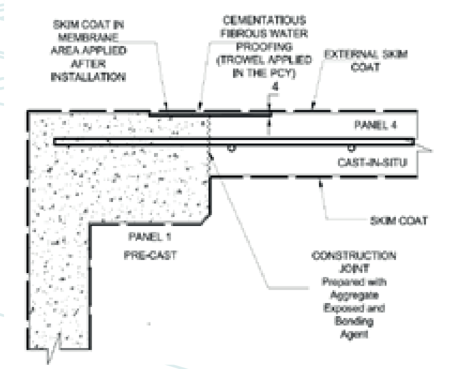
## 1.3 Construction using PVM Method – Case Study in Putrajaya, Malaysia

### *1.3.1 Project overview*

| | | |
|---|---|---|
| Project Type | : | School building |
| Manufacturer and Installer | : | Acre Works Sdn Bhd |
| PVM Type | : | Precast concrete |
| Prefabrication Method | : | From 2D precast concrete wall panels assembled into 3D modules in the factory |
| Number of Modules | : | Classroom – 105 modules |
| | : | Toilet – 18 modules |
| Weight of Module | : | Heaviest – 40 tonne |
| | : | Lightest – 20 tonne |
| Project duration (Design – site finishing) | : | 135 days |

### *1.3.2 Prefabrication method and site assembly*

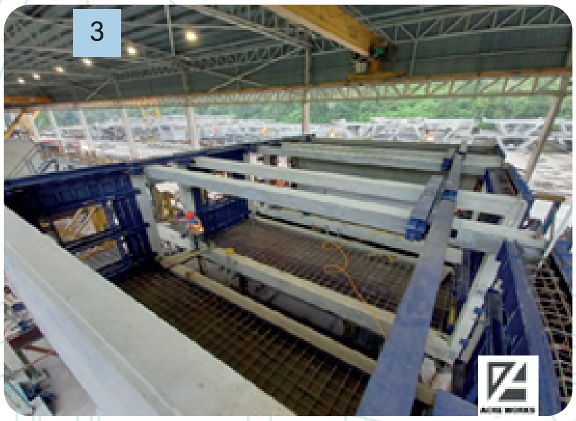



Plan View
Detail of factory assembly from 2D precast wall panel to 3D module

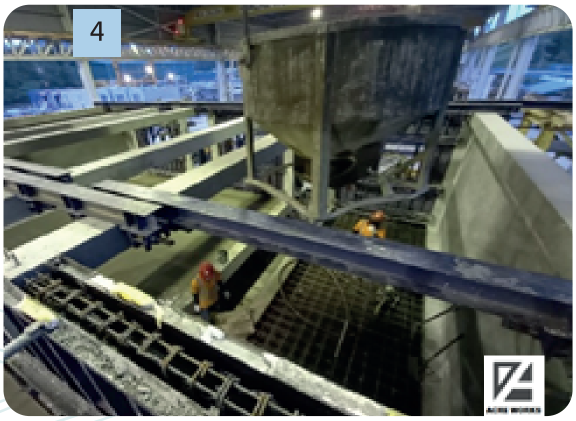

• Wall panel rebar works and concreting at panel casting bay


• Setting up wall panel at module assembly jig.
• Checking panel verticality.



3

- Installing rebar and formwork for front and rear walls and slab

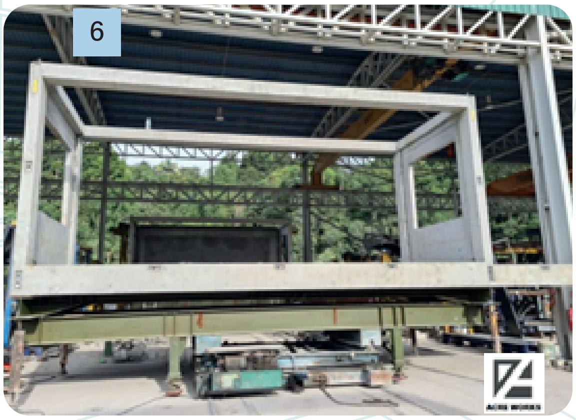


4

- Concreting works inside module

5

- Demoulding



6

- Transferring module to lifting bay.

7

- Lifting module to storage area

8

- Finishing & architecture works interior & exterior module


- Placing module onto low loader


- Module ready for delivery.


- Module installation at site


- Assembly of classroom modules


- Roofing installation


- MEP fitting and final touch up.

*Photo courtesy: Acre Work Sdn Bhd*

# 2.0
# PRODUCTIVITY OF BUILDING CONSTRUCTION USING PVM

# 2.0 PRODUCTIVITY OF BUILDING CONSTRUCTION USING PVM

### *2.1 Measuring PVM Productivity*

Based on a book published by CIDB Malaysia (2020), productivity is defined as the total Gross Floor Area (GFA) constructed per total man-days, where GFA includes the total property square footage, including finished areas inside the property such as common areas, lobbies, stairwells, etc. According to the author, productivity is considered the most important factor in any country's long-term growth, including Malaysia. High-productivity nations can quickly adapt to changes in macroeconomic challenges, as well as fundamental shifts brought on by technological innovations.

Therefore, to find out the productivity rate for PVM construction, a survey was carried out on the listed PVM companies in Malaysia as a case study. During the survey, three types of PVM construction methods were recorded which are (1) precast concrete, (2) metal frame, and (3) hybrid of precast concrete and metal frame.

## 2.2 Details of PVM Projects (Respondents)

### *2.2.1 Case A – Precast Concrete PVM*

a. Sector : Private
b. Type : Residential
c. Gross Floor Area (GFA) : 880204.6 Sqft
d. Days Work/ Month : 26 days
e. Number of PVM : 753 units
f. Project Site : Singapore
g. Factory Location : Johor, Malaysia

### *2.2.2 Case B – Precast Concrete PVM*

a. Sector : Government
b. Type : Social Amenities (Healthcare; School; Education)
c. Gross Floor Area (GFA) : 37009.41 Sqft
d. Days Work/ Month : 26 days
e. Number of PVM : 123 units; (105 units of classrooms & 18 units of toilets)
f. Project Site : Wilayah Persekutuan Putrajaya
g. Factory Location : Selangor, Malaysia

### 2.2.3 *Case C – Metal Frame PVM*

| | | |
|---|---|---|
| a. | Sector | : Private |
| b. | Type | : Other (CLQ) |
| c. | Gross Floor Area (GFA) | : 3408647 Sqft |
| d. | Day Work/ Month | : 26 days |
| e. | Number of PVM | : 896 units |
| f. | Project Site | : Johor, Malaysia |
| g. | Factory Location | : Selangor & Johor, Malaysia |

### 2.2.4 *Case D – Metal Frame PVM*

| | | |
|---|---|---|
| a. | Sector | : Private |
| b. | Type | : Other (CLQ) |
| c. | Gross Floor Area (GFA) | : 873078.8 Sqft |
| d. | Day Work/ Month | : 26 days |
| e. | Number of PVM | : 4288 units |
| f. | Project Site | : Johor, Malaysia |
| g. | Factory Location | : Johor, Malaysia |

### 2.2.5 *Case E – Metal Frame PVM*

| | | |
|---|---|---|
| a. | Sector | : Government |
| b. | Type | : Other (CLQ) |
| c. | Gross Floor Area (GFA) | : 269100 Sqft |
| d. | Day Work/ Month | : 26 days |
| e. | Number of PVM | : 400 units |
| f. | Project Site | : Selangor, Malaysia |
| g. | Factory Location | : Selangor, Malaysia |

### 2.2.6 *Case F – Hybrid PVM (Concrete + Metal Frame)*

| | | |
|---|---|---|
| a. | Sector | : Private |
| b. | Type | : Office |
| c. | Gross Floor Area (GFA) | : 155.0016 Sqft |

d. Day Work/ Month : 26 days

e. Number of PVM : 3 units

f. Project Site : Kuala Lumpur, Malaysia

g. Factory Location : Selangor, Malaysia

## 2.3 Construction Productivity Rate (Respondents)

### *2.3.1 Productivity Grading System*

PRODUCTIVITY = Total GFA (sqft)/ Total Man-Days

= Total GFA (sqft)/ [Total Manpower * Total Construction Period (months)]

| Grades | Productivity rate, x (sqft/man-day) |
|---|---|
| A | $x \geq 10.0$ |
| B | $7.5 \leq x < 10.0$ |
| C | $5.0 \leq x < 7.5$ |
| D | $2.5 \leq x < 5.0$ |
| E | $0 \leq x < 2.5$ |

*Sources: CIDB Malaysia (2020)*

### 2.3.2 *Construction Stages Information*

| CASE | PVM TYPE | CONSTRUCTION STAGE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | DESIGN | | PRODUCTION | | LOGISTICS | | INSTALLATION | | ARCHITECTURAL WORKS & FINISHING | |
| | | Manpower | Duration (month) | Manpower | Duration (month) | Manpower | Duration (month) | Manpower | Duration (month) | Manpower | Duration (month) |
| A | CONCRETE | 4 | 12 | 80 | 6 | 5 | 7 | 30 | 7 | 45 | 6 |
| B | CONCRETE | 27 | 1.96 | 117 | 2 | 12 | 1.15 | 56 | 1.53 | 24 | 2.46 |
| C | METAL FRAME | 5 | 2 | 125 | 6 | 20 | 6 | 90 | 6 | 40 | 6 |
| D | METAL FRAME | 5 | 2 | 30 | 6 | 5 | 1 | 15 | 1 | 15 | 6 |
| E | METAL FRAME | 10 | 2 | 30 | 3 | 15 | 0.5 | 5 | 0.5 | 20 | 1 |
| F | METAL FRAME | 2 | 0.7 | 6 | 0.07 | 3 | 0.0014 | 4 | 0.0028 | 6 | 0.47 |
| | CONCRETE | 2 | 0.23 | 4 | 0.1 | | | 2 | 0.03 | | |

*Note: NA – Not Available*

a) DESIGN - includes Architectural, Structural and M&E drawings.

b) PRODUCTION - includes Formwork, Reinforcement placement & fittings, MEP fittings, Concreting, Plastering, Demoulding, and Lifting to Stockyard.

c) LOGISTICS - includes Loading and Delivery.

d) INSTALLATION - includes Lifting, Assembly, Fittings, and MEP Fittings.

e) ARCHITECTURAL WORKS & FINISHING - including Plastering, Painting, Tiling, etc., for windows, doors, ceilings, staircases, and others.

### 2.3.3 *Overall Project Productivity (Macro)*

| CASE | DESIGN | GFA | | DAYS WORK/ MNTH | PRODUCTIVITY | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SQM | SQFT | | TOTAL MANPOWER | TOTAL MONTHS | MAN -DAYS | *OVERALL PRODUCTIVITY | GRADE |
| A | CONCRETE | 81773 | 880204.6 | 26 | 164 | 38 | 162032 | 5.4 | C |
| B | CONCRETE | 3438.3 | 37009.41 | 26 | 201 | 3 | 15678 | 2.4 | E |
| C | METAL FRAME | 316671 | 3408647 | 26 | 280 | 7.5 | 54600 | 62.4 | A |
| D | METAL FRAME | 81111 | 873078.8 | 26 | 70 | 16 | 29120 | 30.0 | A |
| E | METAL FRAME | 25000 | 269100 | 26 | 80 | 7 | 14560 | 18.5 | A |

| CASE | DESIGN | GFA | | DAYS WORK/ MNTH | PRODUCTIVITY | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SQM | SQFT | | TOTAL MANPOWER | TOTAL MONTHS | MAN -DAYS | *OVERALL PRODUCTIVITY | GRADE |
| F | METAL FRAME | 14.4 | 155.0016 | 26 | 15 | 2.7042 | - | - | - |
| | CONCRETE | | | | 14 | 0.83 | - | - | - |
| | OVERALL | | | | 29 | 3 | 2262 | 0.1 | E |

*Note: Productivity of the project starting from the design stage until the architectural finishes stage.*

### 2.3.4 *On-site Productivity*

| CASE | DESIGN | GFA | | DAYS WORK/ MNTH | PRODUCTIVITY | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | SQM | SQFT | | TOTAL MANPOWER | TOTAL MONTHS | MAN -DAYS | *OVERALL PRODUCTIVITY | GRADE |
| A | CONCRETE | 81773 | 880204.6 | 26 | 75 | 13 | 25350 | 34.7 | A |
| B | CONCRETE | 3438.3 | 37009.41 | 26 | 80 | 3.99 | 8299.2 | 4.5 | D |
| C | METAL FRAME | 316671 | 3408647 | 26 | 130 | 12 | 40560 | 84.0 | A |
| D | METAL FRAME | 81111 | 873078.8 | 26 | 30 | 7 | 5460 | 159.9 | A |
| E | METAL FRAME | 25000 | 269100 | 26 | 25 | 1.5 | 975 | 276.0 | A |
| F | METAL FRAME | 14.4 | 155.0016 | 26 | 4 | 0.0028 | - | - | - |
| | CONCRETE | | | | 8 | 0.5 | - | - | - |
| | OVERALL | | | | 12 | 0.5028 | 156.8736 | 1.0 | E |

*Note: Productivity of the project at site only (Installation and architectural finishes stage).*

## 2.4 *Summary of PVM's Productivity*

| CASE | PVM TYPE | GFA | | PRODUCTIVITY | | | |
|---|---|---|---|---|---|---|---|
| | | SQM | SQFT | *OVERALL | GRADE | **ON-SITE | GRADE |
| A | CONCRETE | 81773 | 880204.6 | 5.4 | C | 34.7 | A |
| B | CONCRETE | 3438.3 | 37009.41 | 2.4 | E | 4.5 | D |
| C | METAL FRAME | 316671 | 3408647 | 62.4 | A | 84.0 | A |
| D | METAL FRAME | 81111 | 873078.8 | 30.0 | A | 159.9 | A |
| E | METAL FRAME | 25000 | 269100 | 18.5 | A | 276.0 | A |
| F | METAL FRAME CONCRETE | 14.4 | 155.0016 | 0.1 | E | 1.0 | E |

*Note: *Overall Productivity - starting from the design stage until the architectural finishes stage.*
***On-site Productivity - installation and architectural finishes stage (site work only).*

From the PVM's productivity analysis, the overall productivity and on-site productivity for PVM using a metal frame (Case C to Case E) show that the rate is more than 10sqft/man-day, and all cases were grade A. This high productivity rate can be achieved because the production and installation of metal frame PVM are much simpler than other types of PVM.

Meanwhile, for PVM using precast concrete, there are two situations; for Case A, overall productivity shows that the rate is 5.4sqft/man-day (grade C), and for on-site productivity the rate is 34.7sqft/man-day (grade A). On the other hand, for Case B, overall productivity shows the rate of 2.4sqft/man-day (grade E), and the on-site productivity rate is 4.5sqft/man-day (grade D). For Case A, this significant difference is due to a large amount of time consumed at the design stage, while for Case B, the difference is minor due to the large number of workers used during production (off-site) and installation (on-site) stage. Concrete PVM needs more workers and consumes more time than metal frame PVM due to wet trade at production and installation stages. During the production stage, more time is needed for bar reinforcement preparation, concrete casting, and the curing process. While at the installation stage, time is needed for connection between modules vertically and horizontally, which involves wet trade jobs when jointing the module.

For hybrid PVM (Case F), both overall and on-site productivity rates are lower than 2.5sqft/man-day (grade E). From the assessment, the main factors that affect the productivity of hybrid PVM are (a) the duration of the project is too long for the small GFA, and (b) the large number of workers used for architectural work at the site.

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Building the Future with
**Prefabrication Volumetric Module**

Productivity and Jointing System

# 3.0 PVM CONNECTION/ JOINTING SYSTEM

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The connection between the structural elements of PVMs is key to the overall structural performance. PVMs, in comparison with in-situ-built structures, incorporate many more connections due to the need to assemble individual elements to form modules, and modules to form the overall building.

## *3.1 Overview of Module's Connection*

Module's connection provides a path for load transfer and load sharing between modules, and the tying elements which allow stacked modules to effectively transfer loads to the foundation. Through load sharing, the connection can satisfy robustness requirements, preventing catastrophic progressive collapse due to local failure. In addition, individual structural member design may require lateral restraint, which is provided by connection between modules. The module's connection also satisfies construction and serviceability requirements. For example, the module's connection may be used to pull modules together during site assembly, closing the gap between them, thereby allowing the use of individual modules which are not perfectly straight or square. The module's connection limits the differential movement between modules which may otherwise cause damage to flashings or constitute loss of serviceability. They also limit overall building sway, which might cause damage to internal linings. According to Lacey, Chen, Hao, & Bi, (2018) module's connection can be grouped into three types: inter-module, intra-module, and module to the foundation as shown in **Figure 3.1** and **Table 3.1**.

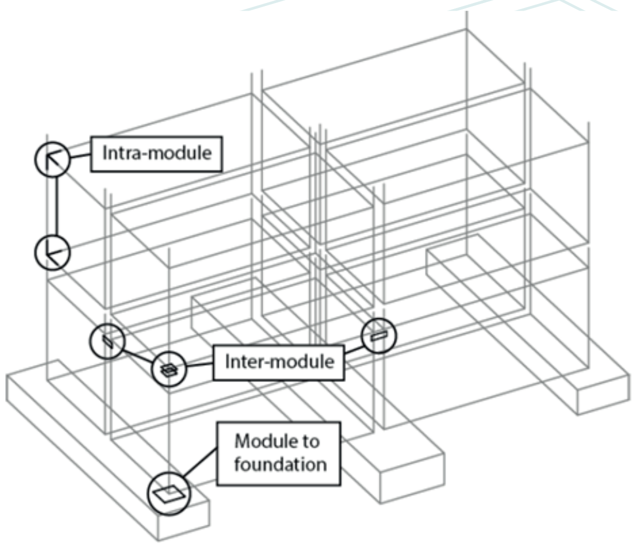


Figure 3.1: Illustration of module's connection types (Lacey et al., 2018).

Table 3.1: Advantages and disadvantages of connection types (Lacey et al., 2018)

| Type | Sub-type | Advantage | Disadvantage |
|---|---|---|---|
| Inter-module | Bolted | Reduced site work; demountable | Access, slotted holes, slip, bolt tensioning |
| | Welded | No-slip, compact, accommodate misalignment | Site work, corrosion, not demountable |
| | Composite (concrete – steel) | Strength, no-slip, compact | Site work, not demountable |
| Intra-module | Bolted | Tolerance for shop assembly, deconstructable | Relatively low moment capacity, ductility, and rotation capacity |
| | Welded | Suited to factory-based construction using jigs to ensure module uniformity | Does not permit rotation, steel members should be designed for hogging moments and axial forces |
| Module to foundation | Chain/ cable/ keeper plate | Low cost | Limited to low-rise construction; tensioning requirements |
| | Site weld to base plate | Rigid connection | Additional trade on-site, hot work, damage to steel corrosion protection system |
| | Base plate – cast in anchor bolts | Ductility | Positioning of cast in anchor bolts, tolerance in steel base plate, corrosion |
| | Base plate embedded in concrete | Full column strength and good ductility | Positioning of column during concrete curing, site welding |

## 3.2 PVM Module's Connection Types

The connection between modules provides vertical connectivity or horizontal connectivity or both vertical and horizontal connectivity. Various research has been conducted by countless researchers to develop multi-types of joints and connections that can be ready to use by the construction industry while using the PVM construction method. Authors such as Lacey et al. (2018); Lacey, Chen, Hao, & Bi (2019b); and Srisangeerthanan, Hashemi, Rajeev, Gad, & Fernando (2020) have compiled and reviewed previous research on PVM jointing and connection, which is elaborated in the next section.

### *3.2.1 Vertical Connectivity Type*

#### a) Bolted End Plate (Bolts on Two Sides) – Connecting HSS

Vertical connectivity is provided through a generic column-column connection using bolts (a simple column end plate connection). The research was done by Styles, Luo, Bai, & Murray-Parkes (2016) and the detail connection is shown in **Figure 3.2.**

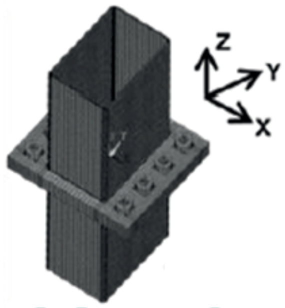


Figure 3.2: Vertical type of connection using bolted end plate

b) Bolted Connection with Plug-in Device – Pre-tension Connection of Column

Vertical connectivity between a stack of modules is provided through pre-stressed strands secured between stiffened sealing plates at the ends of columns. Racking resistance for a stack of modules is provided through the use of shear blocks, which can also facilitate the alignment of modules during assembly. The columns of these modules are concrete-filled tubes, where the plug-in bars are claimed to assist in preventing the concrete from crushing and to provide additional ductility. The research was done by Chen, Li, Chen, Yu, & Wang (2017), and the detail connection is shown in **Figure 3.3.**

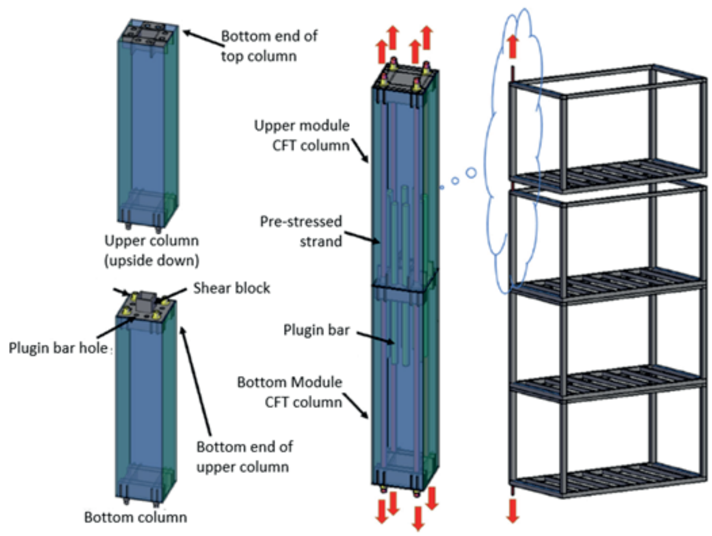


Figure 3.3: Construction detail of pre-tension connecting using bolted connection with plug-in device

c) Post-tensioned inter-module connection

Vertical connectivity is provided through the pre-tensioning of a threaded rod passing through the columns of modules and a plug-in shear key, and is anchored within the zone of inter-connectivity through the aid of access holes. Robustness or tying may be provided by the interaction of the plug-in shear key with the columns, and possibly by the transfer plate as well. The shear keys further provide additional lateral load resistance. It may however be a challenge to insert the threaded rod through the access holes if not sufficiently large, which may subsequently have detrimental localised effects. Additional strengthening may therefore be required. This research was done by Lacey, Chen, Hao, Bi, & Tallowin (2019), and the detail connection is shown in **Figure 3.4**.

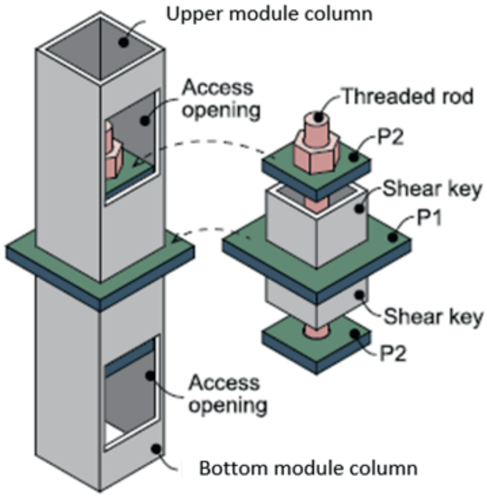


Figure 3.4: Post-tensioned vertical inter-module connection detail

d) Vertical post-tensioned connection

Vertical connectivity is provided through the pre-tensioning of a threaded rod passing through the columns of modules and is anchored at the ends of a stack of modules. Robustness or tying may be achieved through the bolted assembly. A steel box is used for developing shear resistance within a stack and is also used as a guide by having conical formations at the ends. The research was done by Sanches, Mercan, & Roberts (2018), and the detail connection is shown in **Figure 3.5**.

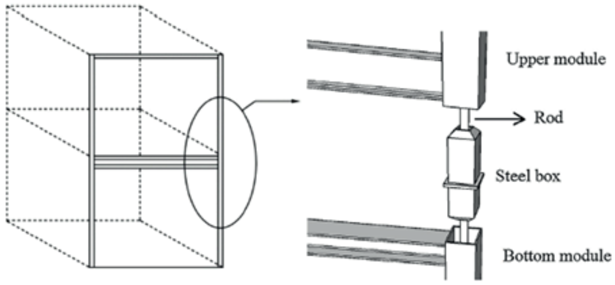


Figure 3.5: Vertical post-tensioned connection detail

### *3.2.2 Horizontal Connectivity Type*

a) Tie Plate – Connecting HSS or Open Steel Section Columns

Horizontal connectivity is provided by bolting steel plates or shop-welded clip angles to the floors at the corners of the modules. Robustness or tying may be provided by the series of bolts or welded clamping the tie plate to the adjacent module (upper and lower module). The research was done by Fathieh & Mercan (2016), and the detail connection is shown in **Figure 3.6**.

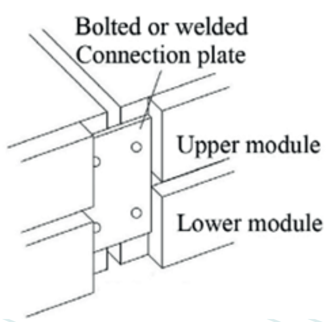


Figure 3.6: Connection using tie plate (bolted or welded)

b) Bolted Side Plate – Connecting HSS

Horizontal connectivity may be provided between adjacent columns of modules via a bolted assembly using a side plate. This connection can be combined with the vertical connection in section 5.2.1(a) from the same researcher. This research was also carried out by Styles, Luo, Bai, & Murray-Parkes (2016), and the detail connection is shown in **Figure 3.7**.

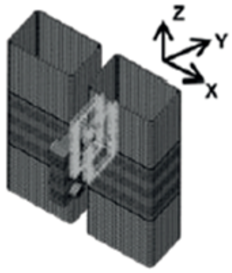


Figure 3.7. Horizontal type of connection using bolted end plate

### 3.2.3 *Vertical and Horizontal Connectivity Type*

#### a) Bolted End Plate – Connecting HSS with Access Hole, or Open Angle Section Columns

Vertical connectivity is provided via a connecting bolt that clamps the column end plates of modules together. Horizontal connectivity is provided via a base plate secured between the roof and floor beams of each adjacent module, and may interact with the connecting bolts. Robustness or tying may be provided via a tie plate connecting each adjacent column. The presence of access holes may require localised strengthening of framing elements. The research was done by Lawson, Ogden, & Chris (2014), and the detail connection is shown in **Figure 3.8** and **Figure 3.9**.

Figure 3.8: Corner angle with welded nut to connect the tie plate

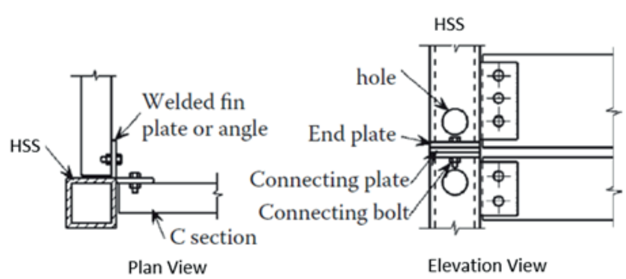


Figure 3.9: Detail bolted end plate connection using HSS

b) Complex Bolted End Plate – Connecting HSS

Vertical connectivity is provided by a bolted assembly that secures column end plates of different forms. Horizontal connectivity is provided through the combined resistance of column end plates. Robustness or tying may be provided by this combined set as well. The research was done by Gunawardena (2016), and the detail connection is shown in **Figure 3.10**.

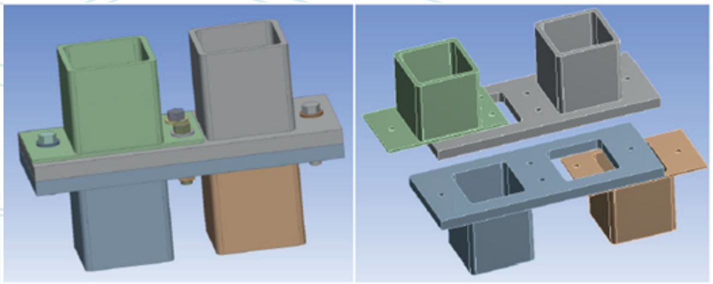

Figure 3.10: Main component of inter-module connection using bolted end plate

c) Bolted Connection Plate – Connecting HSS

Vertical connectivity is provided by clamping the column end plates of each stacked module together through a bolted assembly. Horizontal connectivity is provided via a connection transfer plate secured to the flanges of both the floor and roof beams of adjacent modules via a bolt assembly. Robustness or tying may be provided via the transfer plate. The presence of access holes may require localised strengthening of framing elements. The research was done by K.-S. Choi, Lee, & Kim (2016); K. Choi & Kim (2015), and the detail connection is shown in **Figure 3.11**.

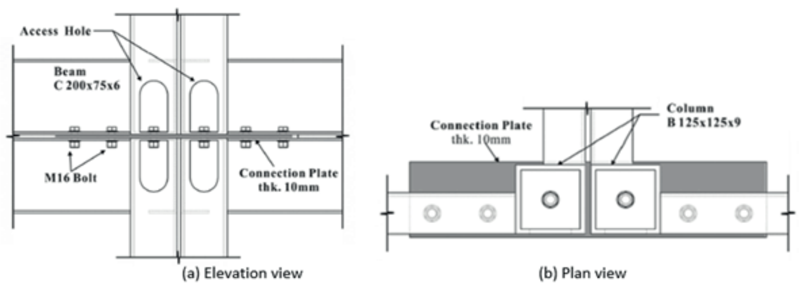


Figure 3.11: Connection detail between modules using bolted connection plate

### d) Steel Bracket – Welded to Corner Column

Vertical connectivity is provided by securing a proposed corner casting through an assembly of bolts. Horizontal connectivity is provided by securing the proposed corner casting through an assembly of bolts. Robustness or tying may be achieved through the proposed assembly of bolts. The research was done by Hwan Doh et al. (2017), and the detail connection is shown in **Figure 3.12**.

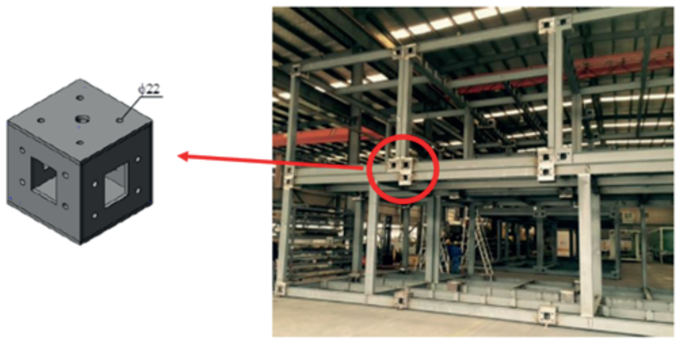

Figure 3.12: Steel bracket connection welded to corner column

### e) Steel Bracket - Bolted or Welded to Floor and Ceiling Beams

Vertical connectivity is provided through a bolted assembly and a singular component made of vertical and horizontal plates. Horizontal connectivity is provided through the bolted assembly, and the singular component made of vertical and horizontal plates. Robustness or tying may be provided through the bolted assembly. The system connects the web and flanges of both roof and floor beams of adjacent and stacked modules. The research was done by Lee et al. (2017), and the detail connection is shown in **Figure 3.13** and **Figure 3.14**.

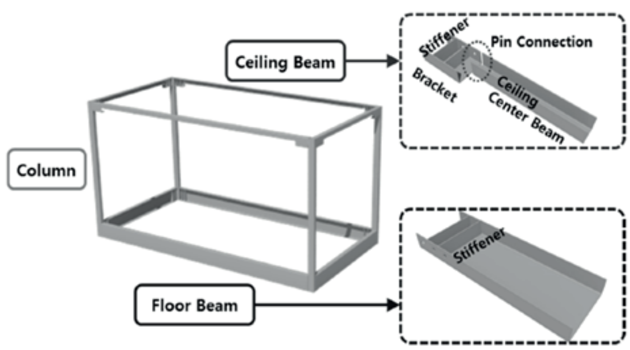


Figure 3.13: Steel frame module.

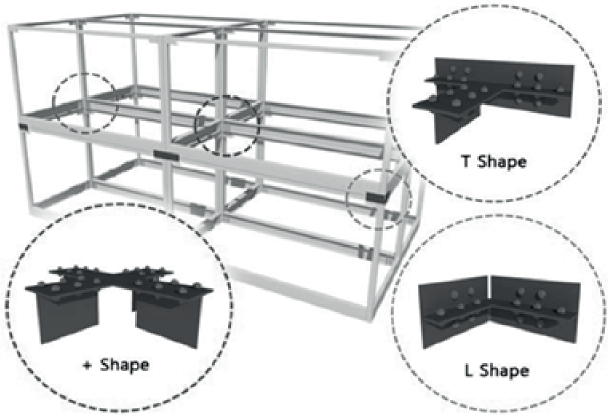


Figure 3.14: Connection attachment and module units

f) Bolted Connection with Plug-in Device – Bolted Interior Steel Connection

Vertical connectivity is provided by a bolted assembly that makes use of long-stay bolts, cover plates, and intermediary plates to secure the floor and roof beams of stacked modules. Horizontal connectivity is provided through a plug-in device that fits into the hollow column sections, much like the ISO stacking cones used for securing freight containers. The transfer plate of the device may act as the medium through which lateral forces will be transferred. Furthermore, the intermediary plates, if one and spans between adjacent beams may also provide lateral force transfer. Robustness may be provided through the interaction of the plug-in device with the hollow column sections and the device's transfer plate. The plug-in device also serves to provide additional shear resistance. The plug-in device inserted into the hollow column sections can function to align modules during assembly. This extensive research was done by Chen, Liu, & Yu, (2017); Chen, Liu, Yu, Zhou, & Yan, 2017), and the details connection is shown in **Figure 3.15** and **Figure 3.16.**

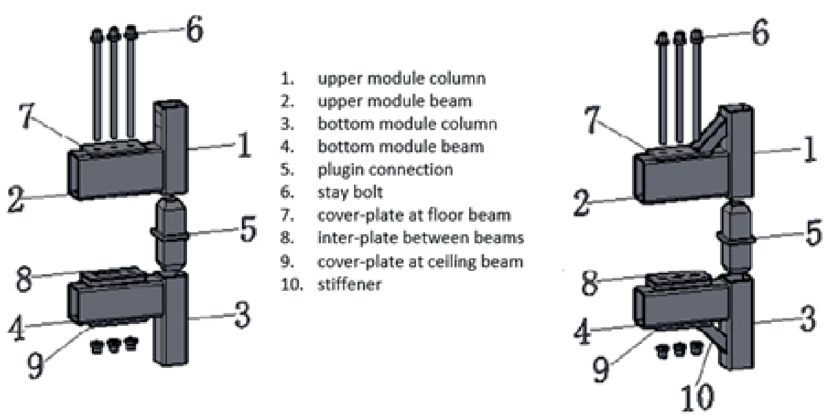


Figure 3.15: Two types of beam-to-beam connections using bolted connection with plug-in device.

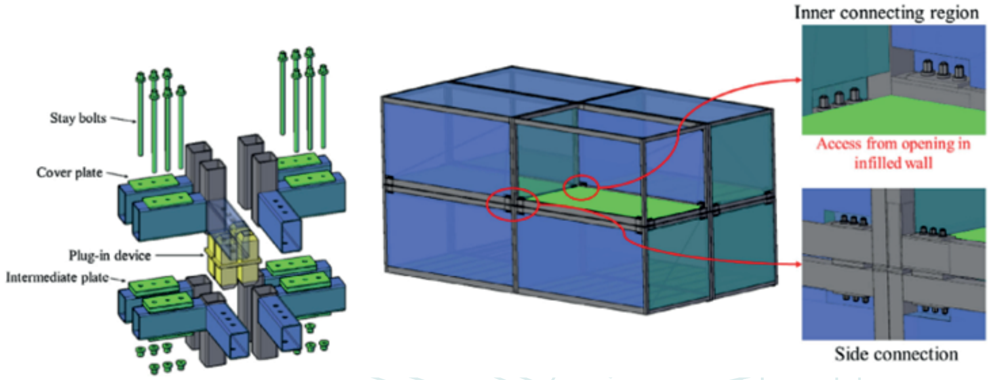


Figure 3.16: Example of connection detailing on MSB Construction

### g) Bolted Connection with Socket-shaped Tenon

Vertical connectivity is provided through an assembly of bolts connecting a singular cruciform assembly of vertical and horizontal gusset plates to the web and flange of both roof and floor beams of stacked modules. Horizontal connectivity is provided through an assembly of bolts connecting the singular cruciform assembly of vertical and horizontal gusset plates to the web and flange of both roof and floor beams of stacked modules. Robustness or tying may be provided by the assembly of web bolts and the horizontal gusset plate, and possibly the interaction between the cones and module columns as well. The cones may be capable of aligning modules during assembly, and provide further shear resistance. The research was done by Deng et al. (2017), and the details connection is shown in **Figure 3.17**.

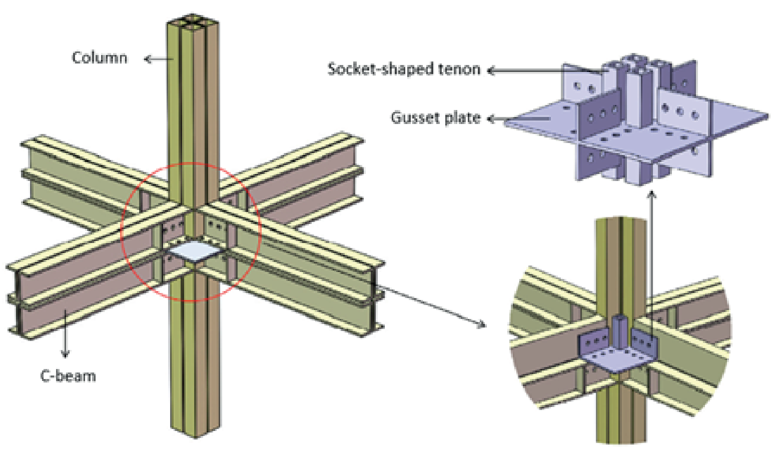


Figure 3.17: Connection configuration for bolted connection with socket-shaped tenon

## h) Bolted Connection with Welded Cover Plate

Vertical connectivity is provided through an arrangement of bolts and a cruciform gusset plate. Horizontal connectivity is provided via the clamped cruciform gusset plate and a horizontal assembly of bolts. The welded cover plate may also interact to provide vertical and horizontal resistance, and possibly tying for robustness. The column elements have been cut out to facilitate access and may result in unwanted localised effects. A plate is proposed to be welded, covering the access hole, which may be beneficial. This connection was developed by Deng et al. (2018), and much is simpler than their previous research. The detail connection is illustrated in **Figure 3.18**.

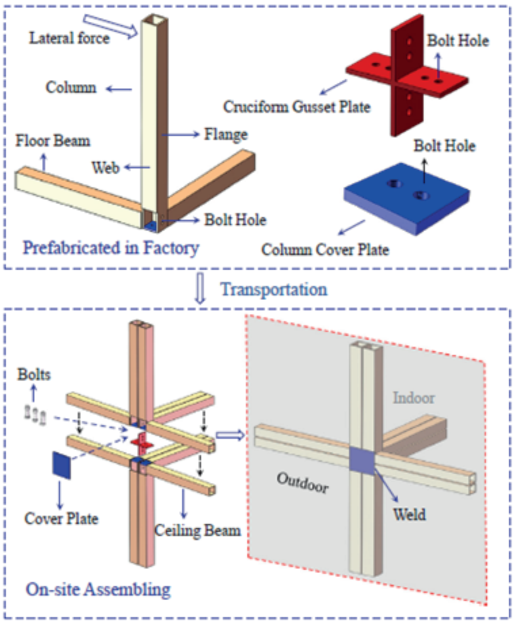


Figure 5.18: Innovative connection using bolted connection with welded cover plate

## i) Novel plug-in self-lock joint

Vertical connectivity is provided through a connector box housing a threaded latching mechanism that engages a threaded stud attached to another connector box upon being triggered by the stud. Horizontal connectivity may be provided through a transfer plate held in position by the stud. Robustness or tying may be provided by the transfer plate. The research was done by Dai, Zong, Ding, & Li (2019), and the detail connection is shown in **Figure 3.19**.

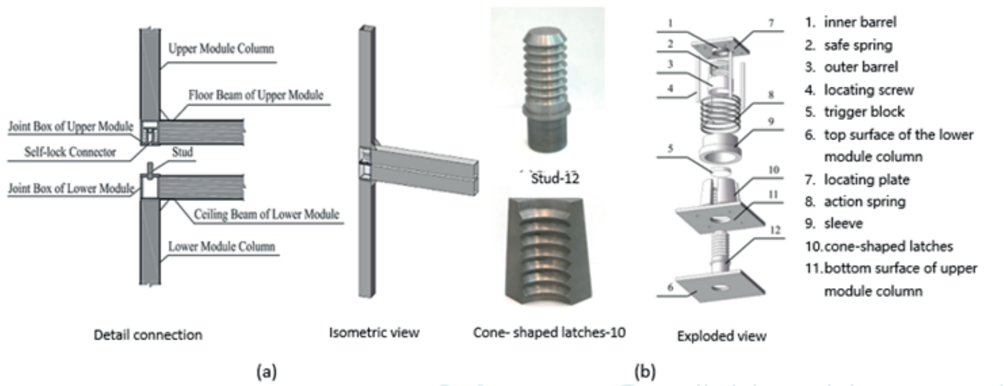


Figure 3.19: Plug-in self-lock joint (a) connection, (b) connector

## j) Shear-keyed grouted sleeve connection

Vertical connectivity is provided through a connector box housing an inner sleeve and transferred from the inner tube diagonally to the outer tube. Horizontal connectivity may be provided through a transfer tie plate held in position by the stud. Robustness or tying may be provided by the inner sleeve. The research was done by Z. Dai, Pang, & Liew (2020), and the details connection is shown in **Figure 3.20**.

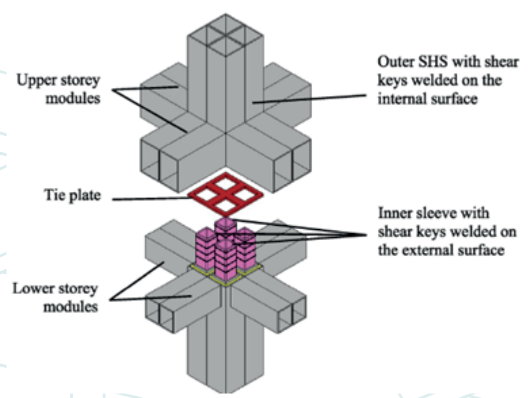


Figure 3.20: Shear-keyed grouted sleeve for inter-module connection

## k) Rotary inter-module connections

Vertical connectivity is provided between corner fittings via a connector which comprises a key like rod, a plate, and a nut. Horizontal connectivity may be provided by welding the plate elements of adjacent connectors to form a singular transfer plate. Robustness or tying may be provided through the overall transfer plate. The research was done by Chen, Liu, Zhong, & Liu (2019), and the detail connection is shown in **Figure 3.21** and **Figure 3.22**.

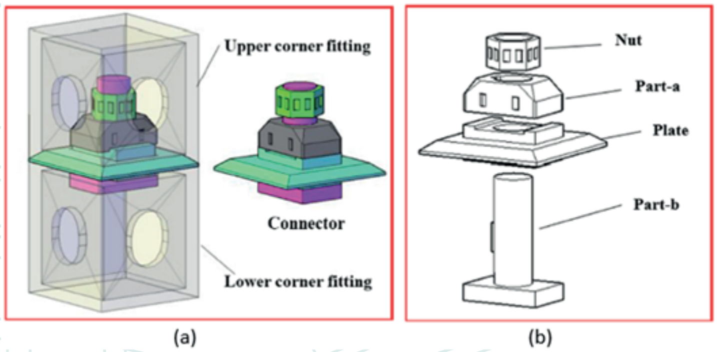

Figure 3.21: (a) Details connection (b) Composition of connector

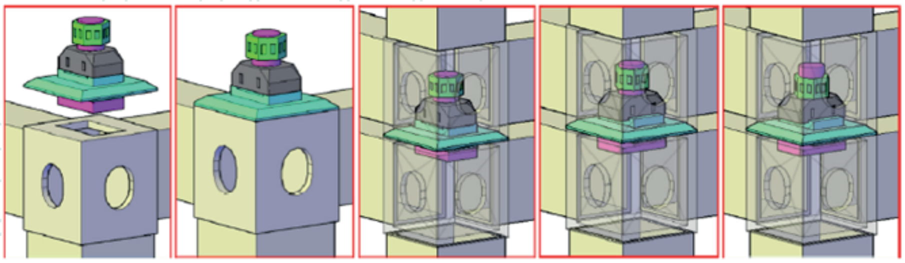
Figure 3.22: Diagram of the assembly process

### l) Modular integrating system using interlocking joint strips

Vertical connectivity is claimed to be provided by a tongue and groove system that is attached to the floor and roof beams of modules. Horizontal connectivity is claimed to be provided by the tongue and groove system that is attached to the floor and roof beams of modules. The system may not be capable of resisting vertical tension. Furthermore, tolerance control and module alignment for assembly may prove to be challenging. The research was done by Sharafi, Mortazavi, Samali, & Ronagh (2018), and the detail connection is shown in Figure 3.23 and Figure 3.24.

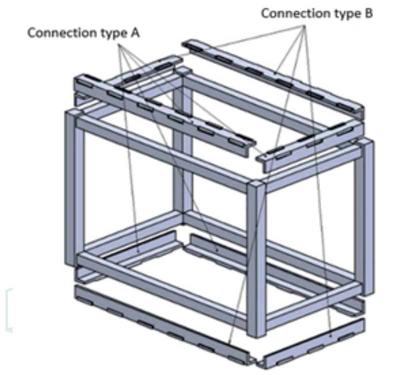

Figure 3.23: Attachment of integrating connection strip to modules.

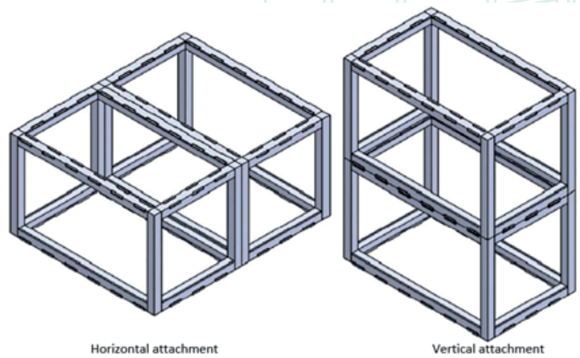

Figure 3.24: Details interlocking inter-module connection

### m) Interlocking inter-module connection

Vertical connectivity is provided through a bolted assembly connecting the end plates of columns together, much like the generic connector considered for demonstration. Horizontal connectivity is provided through a transfer plate held in position by the through bolts used for establishing vertical connectivity and the locating pins used for easing on-site assembly. Robustness or tying may be provided by the transfer plate. The research was done by Lacey, Chen, Hao, & Bi (2019), and the detail connection is shown in **Figure 3.25**.

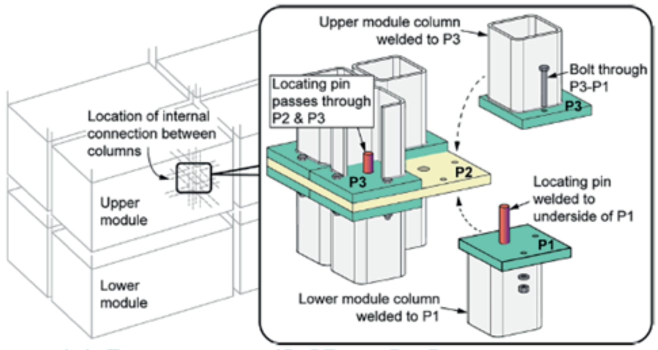


Figure 3.25: Attachment of integrating connection strip to modules.

n) VectorBlocTM system

Vertical connectivity is provided through the securing of corner castings via a bolted assembly. Horizontal connectivity is provided through transfer plates secured onto the corner castings. Robustness or tying may be provided by transfer plates, though other options seem possible where tie plates could be attached to the castings. Conical guides can be attached to the casting to assist in module alignment during assembly. The jointing system was produced by Z Modular (n.d.); and Julian (2015 & 2016), and the detail connection is shown in **Figure 3.26**.

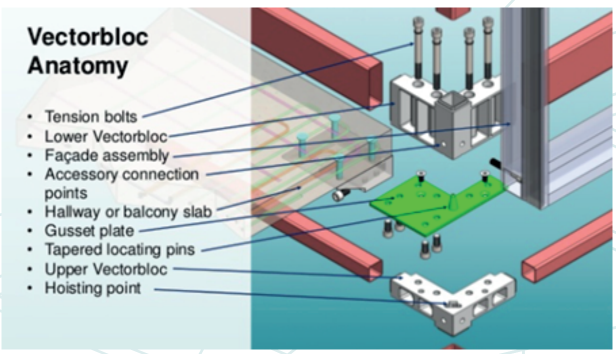


Figure 3.26: Details of Vectorbloc connection

o) Precast concrete module connection (using cast-in-situ strip connection)

The concrete module is made up of a ceiling slab, floor slab, and four walls, and includes the precast part of a semi-precast corridor slab and some protruding bars for horizontal and vertical connections. The horizontal connections can be identified into two types: inter-module and module-to-corridor connections. The horizontal connections between the concrete modules adopt in-situ connecting bars and in-situ concreting to integrate the ceiling slabs at one story into a whole in plane.

Except for the horizontal connection, no special construction details are used to connect the two adjacent walls of the different modules. The horizontal module-to-corridor connections are formed with the construction of a semi-precast corridor slab, which is divided into two parts: the precast part connected with the modules can be used as the cast formwork for the cast-in-situ part. The connecting bars between modules and the corridor slab are used to enhance the connection strength. All of the horizontal connections at the same storey jointly work to ensure that the traditional rigid diaphragm assumption is still available for modular concrete structures. This research was done by Wang, Pan, & Zhang (2020), and the detail connection is shown in **Figure 3.27** and **Figure 3.28**.

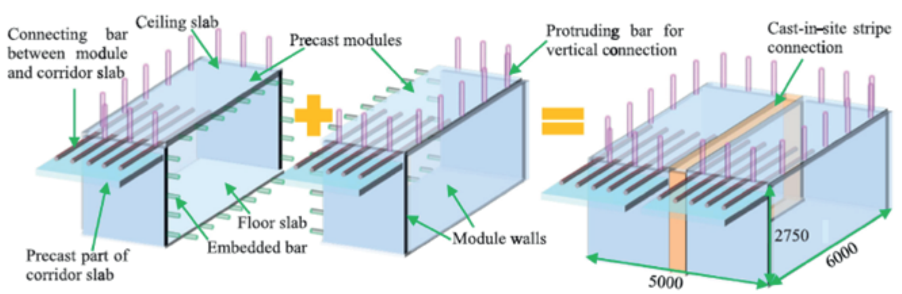


Figure 3.27: Schematic diagram of connection between two precast modules

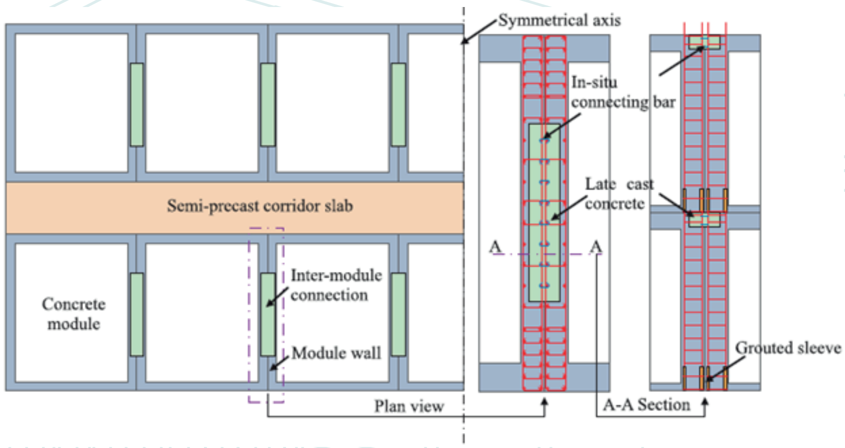


Figure 3.28: Horizontal and vertical connection between modules

## p) Precast concrete module connection (using dowel and grout)

Modular construction connections for gravity-only construction vary from only grout between modules to dowels or ties vertically between modules as illustrated in **Figure 3.29** and **Figure 3.30**. Modular construction in the United Kingdom uses block-outs and through bolts to provide some continuity **(Figure 3.31)**. Gravity connections alone do not allow lateral force transfer and may be inadequate because the loss of a complete module could lead to the progressive collapse of the modules above. Thus, the 2-D analysis indicates that modules must be tied laterally to adjacent modules to distribute the loads. The critical structural integrity condition occurs when a bottom corner module is removed, creating a cantilever situation for the modules above. The connections along the upper modules must be able to develop shear and tension forces such that the modules above the failed unit are restrained. These connections are designed not to yield, but will deform under load. The connection deformation creates effective ductility in the event of a localized failure. Each module is then designed so connections carry a single unit by shear friction. Small slippage allows each module above to engage the shear friction force, and each module is carried individually. The resulting shear friction between modules allows the loads to be distributed laterally and vertically.

Figure 3.29: Example simple gravity dowel connections on grout pad

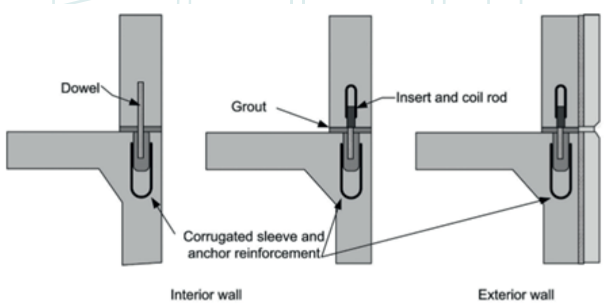


Figure 3.30: Schematic interior and exterior wall connections for use in precast concrete modules

Figure 3.31: Example of block-outs for through bolt connections are seen along module edges

Further modification and improvement were done by Wenke & Dolan (2021) to improve the connection integrity. The first connection concept uses a through bolt to join two adjacent modules to develop a shear friction restraint (**Figure 3.32 (a)**). The connection uses bearing plates to prevent pull-out and dry pack to conceal the connection.

The second connection concept examines the use of a plate to connect adjacent module walls (**Figure 3.32 (b)**). This connection mobilizes the inserts already employed in the basic gravity connections. A corrugated sleeve and anchor reinforcement need to be sufficient to prevent a concrete breakout of the bolt in the event of a module failing below this connection. The exterior corner module requires reinforcement engaged in both horizontal directions. This reinforcement additionally resists forces caused by an edge module failing and provides a cantilever restraint at the top of the module.

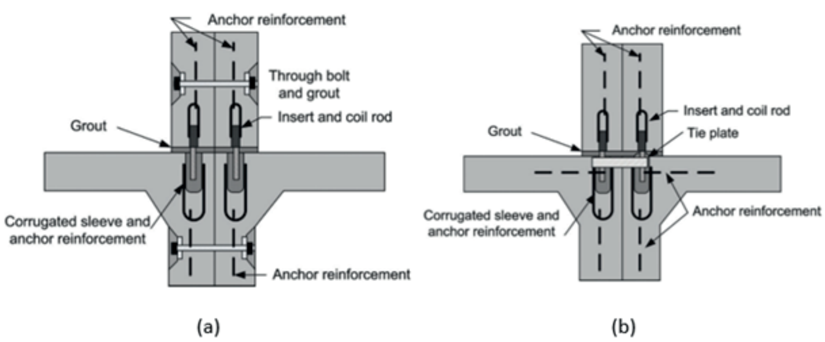


Figure 3.32: (a) Shear friction connection using a through bolt (b) Embedded steel plate integrity connection

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| --- |
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# NOTES

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CONSTRUCTION INDUSTRY DEVELOPMENT BOARD MALAYSIA (CIDB)

10th Foor, Menara Dato'Onn
World Trade Centre,
No. 45, Jalan Tun Ismail,
50480 Kuala Lumpur
MALAYSIA