2016 Modular and Offsite Construction (MOC) Summit
Edmonton, Alberta, Canada, September 29 - October 01, 2016

Prefabricated Prefinished Volumetric Construction Joining Techniques Review

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ABSTRACT
Prefabricated Prefinished Volumetric Construction (PPVC), also known as volumetric modular construction has recently been adopted for high-rise building construction. However, efficient ways of joining the volumetric units on site have not been well developed. The intended high productivity is thus hindered and costs of the PPVC buildings are considerably higher than traditional construction methods. Additionally, issues such as module alignment and water penetration are often exposed during the assembly of modules. Moreover, local code requirements and geographical varieties often lead to different priorities and concerns in the development of joining techniques. This paper focuses on the generic joining techniques adopted in PPVC systems. Three joining methods are presented based on the different locations where the tightening of bolted connection occurs. The methods are evaluated based on the proposed constructability criteria and structural performance. The information gathered is useful for designers and contractors to understand the priorities and issues when developing new joining techniques.

KEYWORDS
Prefabricated Prefinished Volumetric Construction; Joining Techniques; High-rise Buildings;

INTRODUCTION
PPVC systems have been widely adopted in low-rise buildings throughout the world. However, in densely-populated countries like Singapore, promoting application of PPVC systems in high-rise buildings with more than 40 stories becomes the ultimate goal. It will not only resolve the foreseeable decline in the construction manpower but will also support sustainable development in improving environment, saving resources, etc.

Globally, there is only one PPVC building that has been built up to over 30 stories (B2 Atlantic Tower, NYC) (Farnsworth 2014). Also this project has been delayed for more than two years, even more time-consuming than traditional construction methods. The whole project was suspended due to the joining technique issues, where the modules cannot be installed starting from 10th story. The inconsistency between the joining technique design and constructability halted the whole project. Additionally, joined modules are likely to suffer from serviceability issues, such as damaged facades, visual uncomfortableness as in Figure 1. As Harrell et al. pointed out, the most overlooked design of the enclosure of modules is the joints between adjacent modules as in Figure 2. Water leakage issues have been extensively reported in various modular construction projects including B2 Atlantic Tower, Darwin SOHO Apartments (Gardiner 2015; Harrell et al. 2016).

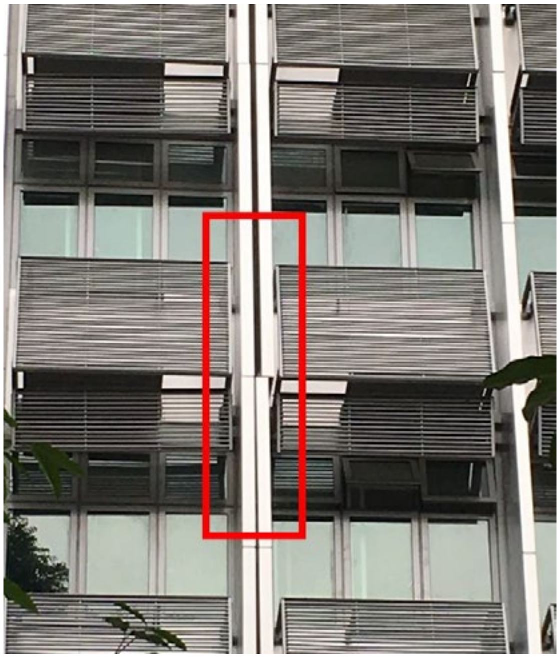


Figure 1. A PPVC project with misalignment result in visual uncomfortableness

Figure 2. Waterproofing insufficient protection of module (Harrell et al. 2016)

The reason why so many problems occur during construction is that for designers the first and foremost consideration is the structural performance. Designers will usually come up with a joining technique and then focus on the evaluation of the structural performance instead of thinking what could possibly happen during construction. However, experience informs us the importance of a more comprehensive consideration other than structural performance:

1. Module Assembly: How easy it is to connect the modules and complete the assembly? Are there any contingent plans for over-sized tolerance? How fast and costly will the modification be? Will the modification significantly compromise the original targeted structural performance?
2. Water Penetration: How to protect the modules from water penetration if it rains during construction, for both the stacked and unstacked modules? Also the joints need to be protected from corrosion.
3. Inspection Access: Are there any accesses for inspection and maintenance? If so, will it be cost-effective?
4. Fire-protection Cost: How will the joining technique have impact on the fire-protection both within the module and the joint area?
5. Work Environment Safety: Is additional scaffolding needed? Will the worker be working in hazardous situation?
6. Trades Number: How many trades on site are needed other than professional steel workers?
7. Module Access Holes: Will the connection of the modules result in damage in module finishes?
8. Architectural Flexibility: How much flexibility the joining technique can provide to architectural layout of the modules and the whole building?

Item 1 is critical for all projects as failing to resolve it will directly result in failure of every project. Item 2 is especially demanding in tropical places like Singapore where the rain pours down almost every single day; once the water penetrates into the modules or joint area, it is almost impossible

to take any remedies. Item 3 should be strictly enforced to guarantee the safety and reliability of the new developed PPVC systems, especially when adequate knowledge and official guidelines are not available. For example, regular inspection is mandatory in Singapore (BIP Checklist for PPVC 2016). Item 4 is an important consideration in Singapore as the fire-protection is very expensive. It will be very cost-effective if the design of the modules and joining techniques could be compatible to allow for utilization of some innate fire resistance of structural component like concrete filled columns (CFC). However, some joining techniques rule out the possibility of using CFC. Item 5 points out one of the main benefits of PPVC connection, safe working environment, might be compromised if external scaffolding are needed. Usually the scaffolding if used has to be the kind that can be lifted with the stacking of modules. Hence it is very costly and time-consuming to build on site. Item 6 plays a significant role in determining the costs and speed of module assembly. For example, the Atlantic Yards Buildings B2 in Brooklyn, NY, adopted pure steel solution by using the lateral load-resisting bracings instead of traditional concrete cores to save costs and time (Farnsworth 2014). Item 7 will be raised if accesses on the facades, wall or slab for connection are needed. However, these accesses can be used for inspection and maintenance, and thus have their own advantages. Item 8 is important for architectural design as some joining techniques cannot be applicable to all situations as will be illustrated later.
The above-mentioned concerns are the criteria and priority sequence used in this paper to review the joining techniques. The structural performance is also evaluated as it directly determines the applicability of a joining technique to be used in high-rise buildings.

PPVC MODULE ASSEMBLY

In this paper, corner-supported modules and their joining techniques are discussed. The following is a typical structural layout of corner-supported module with major structural components only (excluding purlins, bracings, walls and slabs) as in Figure 3 and Figure 4. There are mainly five kinds of module joints based on their respective locations as shown in Figure 5.

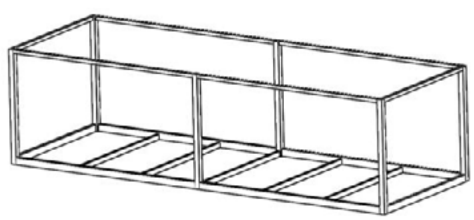


Figure 3. Isotropic view of a typical steel module chassis

Figure 4. Isotropic view of assembled modules

JOINING TECHNIQUES REVIEW

Three types of most widely used joining techniques are evaluated based on a typical joining technique of their types. Pros and cons will automatically be grouped by the above defined eight criteria.

External Plate Connection (Figure 6)

An external plate is bolted to the upper parts of the columns of the two bottom module and the lower parts of the columns of the two top modules. The bolting can be realized by using blind bolts, pre-welding the nuts to the inner surfaces of the columns or by creating access holes on the columns near the bolting holes. Usually there will be an interlocking system buried inside for assistance in locating the modules and resisting horizontal shear.

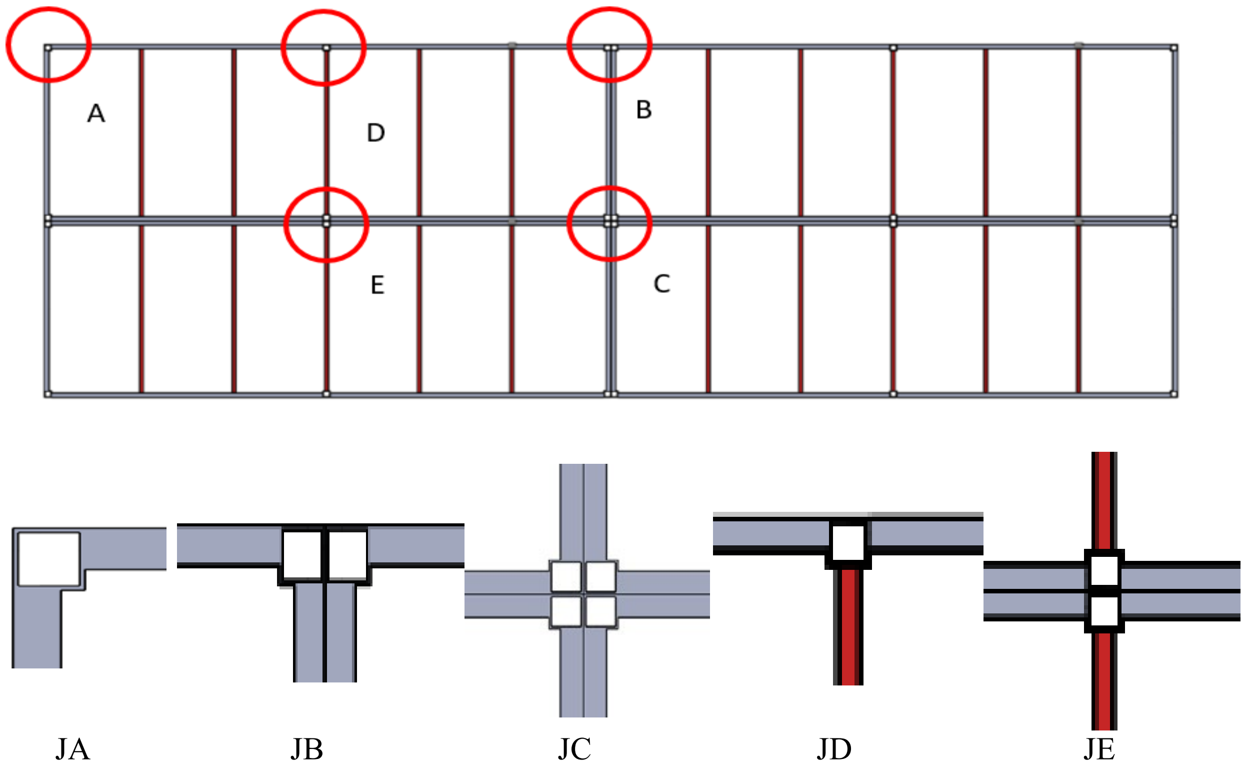


Figure 5. Plan view & five types of module joints

Constructability Pros:

1. Module Assembly: Connection can be easily done on site. If over-sized tolerance appears, modification can be easily made on the external plate by using slotted holes to continue the connection and the cost is minimal. Strength reduction in plate would not be significant as thickness of plates can be increased. If there are changes in column section size, it is easy to make adjustment for connection.
2. Module Access Holes: There is no need to create access holes on the facades, walls, or floors. No additional finishes work on site.
3. Fire-protection Cost: The connection has no impact on module internal fire-protection. The only difficulty lies in fire-protection of the joints as they are at the perimeter of the buildings.
4. Trades Number: Only steel trades are needed for module assembly.

Constructability Cons:

1. Water Penetration: External plates have to be exposed during construction and will be only covered by paint coating to protect the steel from corrosion. However, internal protection can hardly be made.
2. High-cost in Inspection and Maintenance: All the exposed joint pieces need to be covered by fire-protection and water-proofing materials. Especially for very humid environment, the moisture will go inside the column and lead to corrosions unless the joint can made watertight. If the inner parts of the joint were to be corroded, the costs of repair can be enormous.

3. Work Environment Safety: External climbing scaffolding is required for workers to handle the bolting connection. This not only adds to time consumption and construction costs but also compromise the safety of working environment.
4. Architectural Flexibility: It is only applicable for joint JA, JB, and JD. The architectural arrangement of the modules will be limited unless internal joints JC, JE can be resolved with other type of joining mechanism.

Structural Performance Evaluation:

1. Pre-welded nuts on the inner surface of the columns are not reliable. It is difficult to tighten the bolts and the bolts will become loose with time. Moreover, inspection and monitoring of this type of bolted connection cannot be accomplished.
2. Low vertical shearing resistance: In terms of shearing resistance, horizontal shearing forces might be adequate considering the assistance from shear keys, however, the vertical resistance can only be provided by the external plate. Any unbalance settlements or uplifting can easily result in failure of the joint.

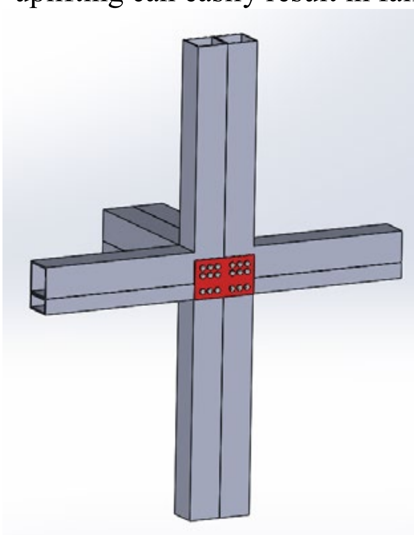
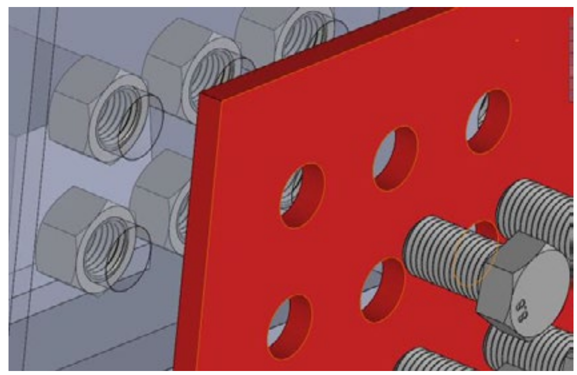



Figure 6. External plate connection with nuts pre-welded to the inner surface of the column

Long Bolts Connection at the Beam End (Figure 7)

Figure 7 shows a type of connection that utilizes long bolts for bolting the floor beams of the upper modules to the ceiling beams of the lower modules. Lateral connection of the modules is provided by a gusset plate. Also shear keys or sleeves can be welded to the gusset plate to resist horizontal shear. There are two ways to tighten the long bolts. One way is using traditional nuts to tighten the bolts at the bottom of the ceiling beam. The other way is to tighten the bolts using embedded threads within the ceiling beam ends which are usually steel blocks welded to the ceiling beams.

Constructability Pros:

1. Module Assembly: If the ceiling beam end has a mechanism to lock and tighten the bolts, the connection is relatively easy. If not, the workers will have to go up and down into the modules and bolts tightening will be very troublesome. Modification on site will be difficult. However, with the internal plugin mechanism, the tolerance should be controlled. It is only likely that the bolting holes could be offset and would need to be modified.
2. Inspection Access: Inspection can be easily conducted as the access to the connection is available even after all the modules are installed.

3. Fire-protection Cost: The connection has general no impact on module internal fire-protection. Only the access holes need to be further covered by fire-protection materials.
4. Work Environment Safety: All the work connection can be completed within the modules and right on top of the modules. Safety is enhanced compared to traditional construction methods.
5. Architectural Flexibility: This type of joint is applicable to all kinds of scenarios.
6. Trades Number: Only steel trade is needed for module assembly.

Constructability Cons:

1. Water Penetration: With the access holes created on walls, it is very likely that water penetration would occur during construction. Measures to protect the joint area from water intrusion are critical and need to be further developed. If not, cost of repair will be high.
2. Module Access Holes: If the partition walls and facades are in obstruction, connections cannot be completed without knocking off a portion of the walls and that could result in repetitious work and more costs.

Structural Performance Evaluation:

1. The vertical shearing resistance is relatively strong as it is strengthened by the additional plates added to the beam ends as the green plates shown in Figure 9.
2. If load-resisting capacity is not large enough, it is easy to add another row of bolts to increase load resistance.
3. Stress concentration might be significant. An optimization design is needed to have smoother load transfer.

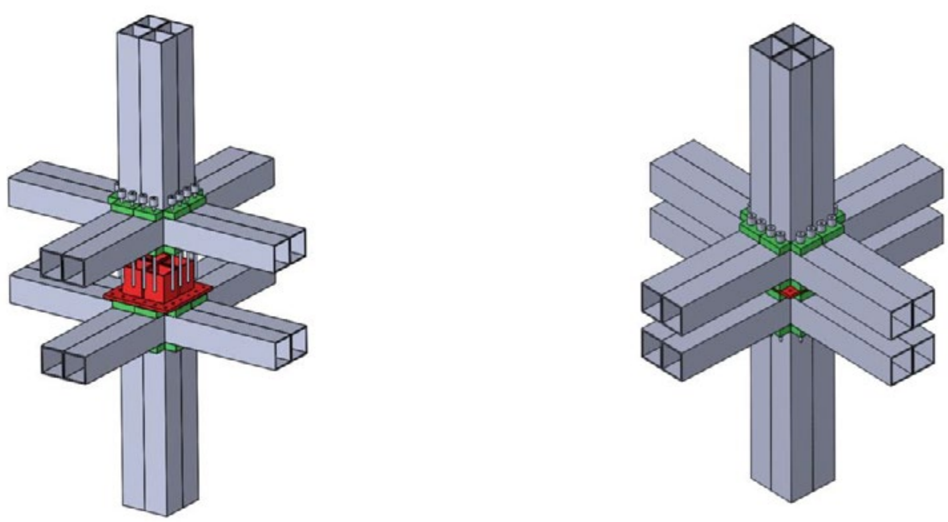


Figure 7. Long bolts connection on the beam with gusset plate and insert sleeves

Vertical Reinforcements Connection (Figure 8)

This type of connection has been used in constructing lower-rise buildings, called post-tensioned modular system (PTMS) (Zheng et al. 2011). For high-rise buildings, the connection can be modified as shown in Figure 8. Reinforcements are locked to the plate by specially designed rebar tighten couplers. The rectangular hollow section (RHS) sleeves are welded to the connecting plate to assist in locating the upper modules and providing shearing resistance. Rebar splices are used to extend the reinforcements. Holes for concrete casting can be easily created by modification.

Constructability Pros:

1. Water Penetration: If the modules themselves are designed against rainwater penetration, this type of connection will not be influenced by water much especially when the columns are filled with concrete.
2. Module Access Holes: There is no need for additional access for connection. The architectural appearance is very neat.
3. Fire-protection Cost: Fire protection and waterproofing can be provided by the concrete filled column to a certain extent. It will save a lot of costs especially for places where fire-protection is very expensive.
4. Architectural Flexibility: This type of joint is applicable to all kinds of scenarios.

Constructability Cons:

1. Module Assembly: Dealing with reinforcements are difficult, which adds to the difficulty in construction. Using reinforcements results in laborious work on site and slows down the overall construction speed.
2. Work Environment Safety: It is difficult and dangerous to stack the upper modules with reinforcements protruding underneath.
3. Trades Number: Casting concrete invites wet-work on site.
4. Inspection Access: Inspection cannot be made once the modules have been installed. Unless casting concrete or using special waterproofing materials, the corrosion within the column can be a significant issue.

Structural Performance Evaluation:

1. Limited moment resistance: The columns are in contact, but not connected to the connection plate below. When the columns are subjected to horizontal shearing force, the resulted moment will be resisted by the reinforcements. The uplifting of the modules can significantly speed up the failure of the joint by adding to the horizontal shear in reinforcements.

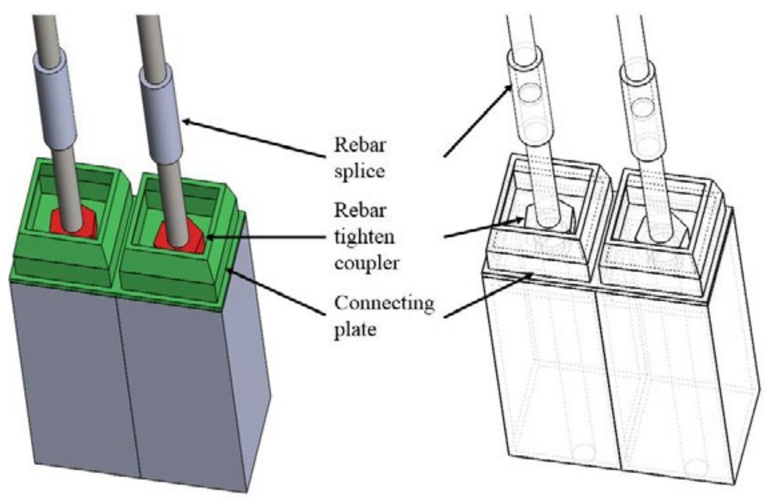
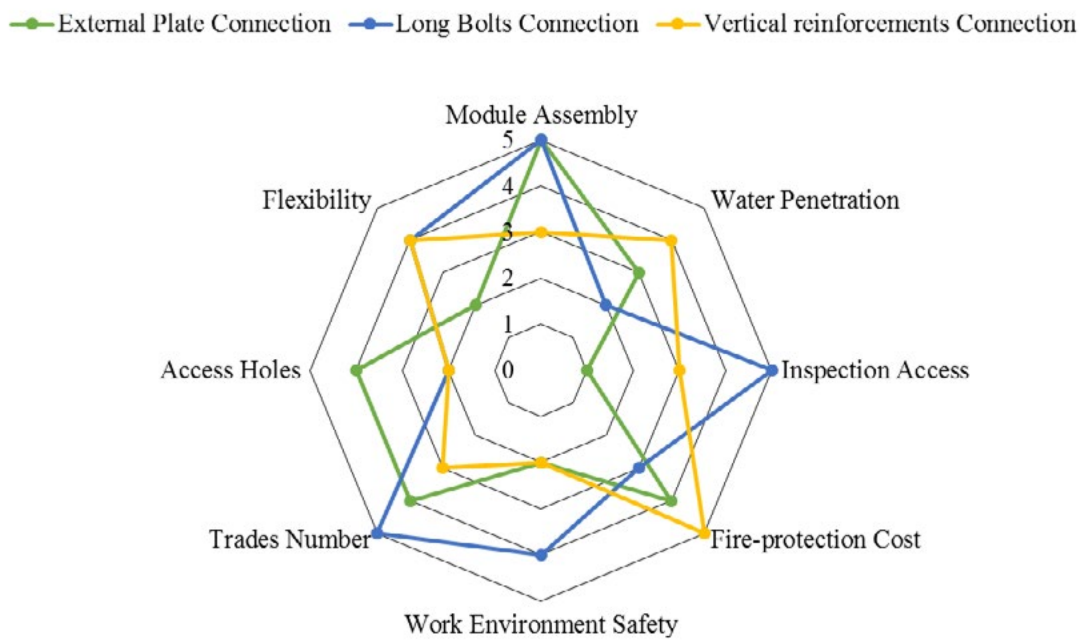


Figure 8. Modified PTMS Joining Technique

CONCLUSION

From the above analysis, we can summarize the pros and cons and compare the joining techniques according to the eight criteria as in Chart.1. The scores are given on a 1~5 scale based on the degree of satisfaction of purported criteria. It can be observed that each joining technique has its own pros and cons. The following chart can be used as a tool in the selection of joining techniques based on targeted requirements. However, the grading of the each criteria tends to be subjective and biased. Hence it is necessary to establish a stringent and detailed evaluation system to help engineers and their client to decide on which system best suits their needs. With more research and disclosed information of PPVC joint, a more detailed and comprehensive evaluation system is expected to be formed to guide the directions of the optimizing and developing PPVC joining techniques.

Chart. 1 Joining Techniques Comparison Radar Chart



ACKNOWLEDGEMENTS

The research is supported by the National Research Foundation Singapore, Sembcorp Industries Ltd. and National University of Singapore under the Sembcorp-NUS Corporate Laboratory.

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