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Steel concrete composite systems for modular construction of high-rise buildings

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ABSTRACT

Modular prefabrication technology promotes off-site manufacturing of modules and on-site assembly by improving the construction efficiency, safety and productivity. However, the joining of individual modules needs special connectors that must be fast to install and robust enough to ensure structural integrity. The restrictions on the overall dimension and weight of the modules for lifting and transportation provide the impetus to develop a more efficient structural module system that is lightweight and fast to install. This paper discusses the design and construction challenges of existing modular construction of high-rise buildings and provides solutions to resolve these challenges. A novel lightweight steel-concrete composite system is introduced to reduce the weight of the module without compromising the strength and stiffness. To increase the available headroom, a slim floor system is proposed to reduce the floor-to-floor depth and ensure the integration of buildings service within the structural zone. High strength concrete is used as an infill material for tubular columns to maintain the same column size to avoid complex joining details involving modules with different column sizes. Long-span steel concrete composite modular system is proposed to reduce the number of joints and columns for fast track construction. A fast and easy joining technique is developed to ensure fast installation of modules. Inter-module joints are modelled as semi-rigid to capture the realistic joint behaviour in global analysis to ensure the structural integrity and overall stability of the building.

1. Introduction

Conventional construction methods that use cast in-situ structural elements and brick walls are still widely used due to relatively low labour cost in some countries. However, the low productivity of such construction methods have impeded economic growth in construction and they are losing their financial advantage with increasing labour costs [1]. At the same time, expanding urban population calls for more high-rise buildings. Coincidently, a good design practice of high-rise buildings is to embrace simplicity, standardization, repetition, and economy of scale. This renders the high-rise buildings to be intrinsically modular by off-site factory production [2–5].

To overcome these challenges, modular construction has been encouraged in Singapore whereby building modules are constructed off-site before being assembled on-site to form a building. Prefabricated Prefinished Volumetric Construction (PPVC) is a specific type of modular construction where the internal elements of the modules (walls, floors and ceilings, mechanical, plumping and electrical, etc.) are prefinished before the modules are installed [6]. With the advantages of higher construction speed, productivity and quality control, modular construction has been adopted in many sectors of the building industry, such as residences, hotels and hospitals by several countries over the last 20 years.

In recent years, Singapore has also shown great effort to promote modular construction in local projects to achieve productivity improvement in terms of construction time and manpower. Since 2014, the use of modular construction in selected public residential projects has been made mandatory [7]. Its benefits have been proven in the successful launching of pioneer modular construction projects in Singapore: (a) Crowne Plaza Hotel Extension, Changi Airport, and (b) NTU North Hill Residence Hall as shown in Fig. 1. It is reported that both projects have achieved time savings of up to 6 months and on-site manpower savings of up to 40%. These projects give confidence to the industry, government, and public on this new technology. It is projected that by 2019, 35% of newly launched housing board projects will be built using modular construction. Table 1 summarizes the current modular construction projects in Singapore.

The idea of modularization is compatible with the design of high-rise buildings which encourages design standardization and repetition. Currently, the cost of modular construction is approximately 15% more

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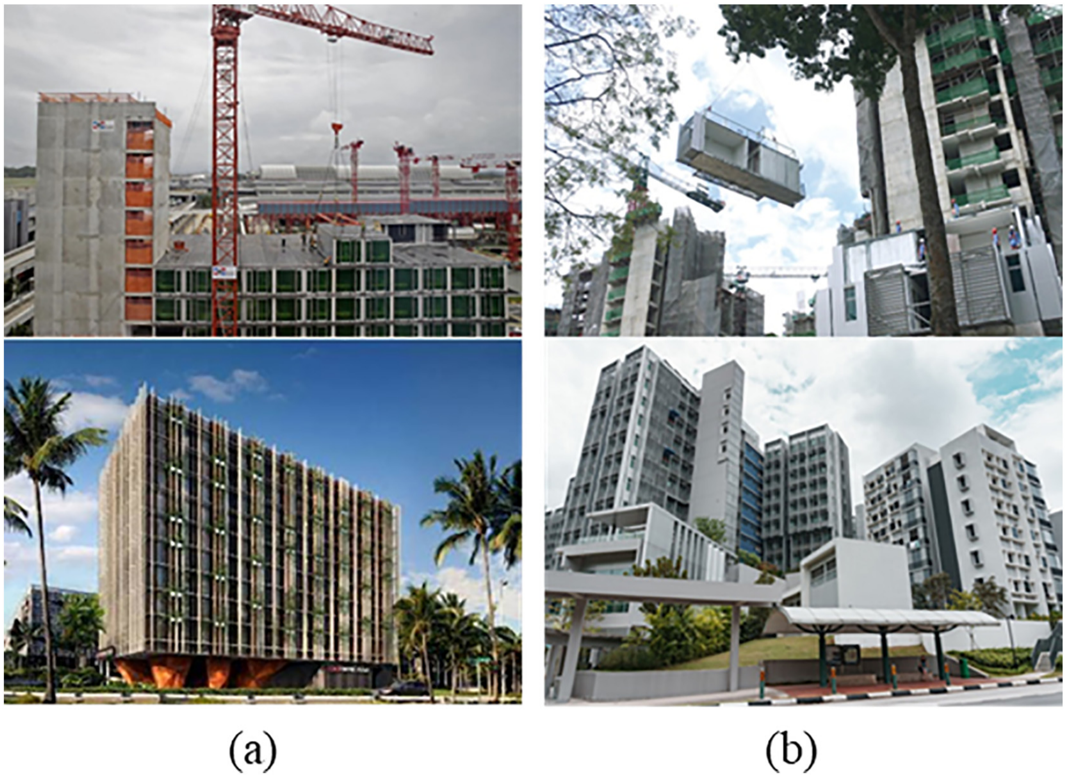


Fig. 1. Pioneer modular construction projects in Singapore (a) Crowne Plaza Hotel Ext @ Changi Airport, and (b) NTU North Hill Residence Hall (Photographs courtesy of Dragages and of Office of Development & Facilities Management, Nanyang Technological University for Nanyang Crescent).

Table 1
List of modular construction projects in Singapore.

	Project name	No. of storey	Type of module	Function
1	Crowne Plaza Hotel Ext @ Changi Airport	10	Steel	Hotel
2	NTU North Hill Residence Hall	13	Steel	Hostel
3	NTU Nanyang Crescent Hostel	11 & 13	Steel	Hostel
4	Nursing Home (Woodlands)	9	Steel	Nursing home
5	JTC Space @ Tuas	9 (L7-L9 are PPVC)	Steel	Industrial
6	The Wisteria Mixed Development	12	Steel	Private residential
7	Brownstone Executive Condominium	10 & 12	Steel	Private residential
8	Senja Polyclinic	12 (L7-L12 are PPVC)	Steel	Polyclinic, nursing home
9	Bukit Batok Qingjian	16	Concrete	Private residential
10	Lake Grande Condominium	17	Concrete	Private residential
11	Parc Riviera Condominium	36	Concrete	Private residential
12	The Clementi Canopy Condominium	40	Concrete	Private residential
13	Tapestry Condo	15	Concrete	Private residential
14	Hillview Rise Condo	NA	NA	Private residential

than traditional construction unless the benefit from the economy of scale can be fully achieved. By building high-rise, the cost-effectiveness of modular construction can be enhanced due to the increased number of repeated modules with repetitive architectural plan and structural layout. Nonetheless, most of the existing modular construction projects are only constructed up to 20 storeys, as shown in Table 1. This summarizes modular buildings constructed in the past five years. Because of its novel structural form that consists of many inter- and intra-module connections as compared to conventional construction method, the construction industry is not confident and unfamiliar in implementing such technology, hence hindering modular construction from being feasible for high-rise buildings [8,9].

Until recently, the Clementi Canopy Condominium (see Table 1) was constructed to 40 storeys but it is made of concrete modules with load bearing walls. At the present, the construction industry is keener to adopt concrete modular construction which utilizes load bearing wall because of smaller dimensions of the modular units, less stringent requirement in construction tolerances, better fire performance and better water-tightness. Despite the fact that steel modular construction is a lighter option compared to concrete, it is not popular in high-rise residential buildings partly due to fire protection and corrosion issues. This paper highlights the existing design construction issues of using modular construction for high-rise buildings and proposes solutions to address these issues. A novel steel-concrete composite system is proposed as a viable and more efficient system that inherits the merits of concrete modular construction of being durable, fire-resistant, waterproof, and sound-proof. In addition, it carries the advantages of structural steel system of being flexible in architectural design, integration of building services, lightweight, long span and fast assembly.

2. Modular construction and its limitations

There are two common types of modular systems with different types of load path. Load bearing wall modules are commonly used in

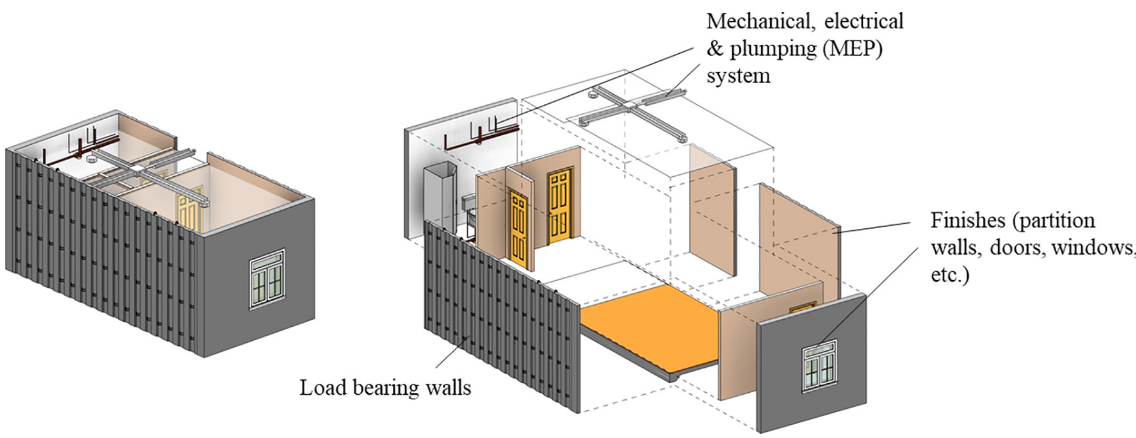


Fig. 2. Load bearing modular system.

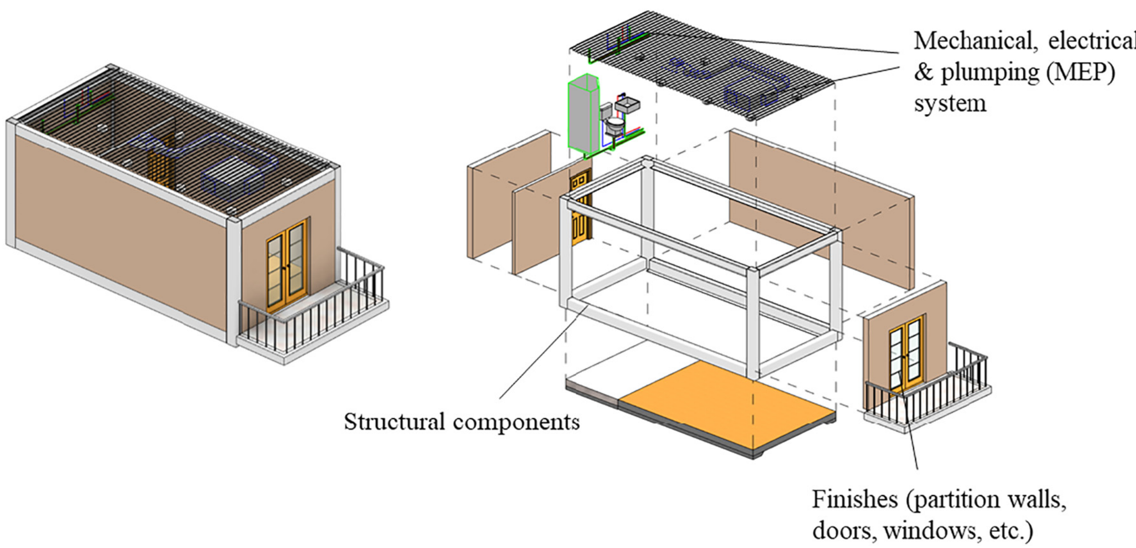


Fig. 3. Corner supported modular system.

concrete building, in which the concrete walls are used to transfer gravity loads to the foundation, as well as resisting the lateral loads as illustrated in Fig. 2 [10]. The other type of modular system is based on corner supported modules, which are generally made of steel in which the gravity loads are transferred to the slab, then to the edge beams and corner columns and to the foundations [10]. The lateral load is resisting by separately braced frames or reinforced concrete core wall. Generally, the weight of a steel modular unit is about 15 to 20 t, which is 20 to 35 % lighter than a concrete modular unit with weight of about 20 to 35 t. Moreover, steel modular systems have more flexibility in architectural design owing to the open space framing system and larger module sizes with beam span ranging from 6 m to 12 m [11]. This leads to a smaller number of modules and connections in steel modular system as compared to those using concrete. The construction speed of steel modular system is also faster as it commonly involves bolted connections whereas concrete modular system often requires in-situ grouted joints.

However, steel modular construction may have durability and fire resistance issues depending on the construction system. In addition, periodic inspection on bolted connections in steel modular systems is often required to ensure their integrity is not compromised by corrosion in the service life of the building [6]. Therefore, steel modular systems are commonly used in institutional and student residence buildings, as listed in Table 1, whereby a larger open space is necessary and periodic inspection can be conducted more conveniently. Inspection points shall be strategically positioned at common area for the ease of inspection [6]. Concrete modular systems are preferable in residential buildings because they are perceived to have better sound and thermal insulation and ease of maintenance. Concrete modules are less stringent in terms of manufacturing and construction tolerances as their joints are made by grouting the gaps between the modules and hence on-site correction can be done during module placement [11].

Prefabricated prefinished volumetric construction (PPVC) encourages high prefabrication rate as the modules are completed with finishes and mechanical, electrical, and plumping (MEP) in the controlled environment [6,12]. The construction sequence of a modular unit consists of six phases as demonstrated in Fig. 4. Firstly, the structural system of a module is assembled in the factory. This is followed by integration of MEP as well as interior and exterior finishes into the main structural system as shown in Fig. 4(b) and (c). Thereafter, the module is transported to the site by truck, as displayed in Fig. 4(d), according to construction schedule. Generally, there is limited space at the site to store the completed modules. Therefore, the arrangement of module transportation to site needs to be aligned with module on-site installation. Lastly, Fig. 4(e) shows the stacking of modules at the construction site using a tower crane. In most of the modular construction projects, the modules are generally placed on top of a cast in-situ concrete podium that may serve as a car park, public space, etc. The manufacturing, transportation and installation of modules need to be well scheduled such that the podium and the lateral force resisting system (LFRS) such as core wall can be constructed first.

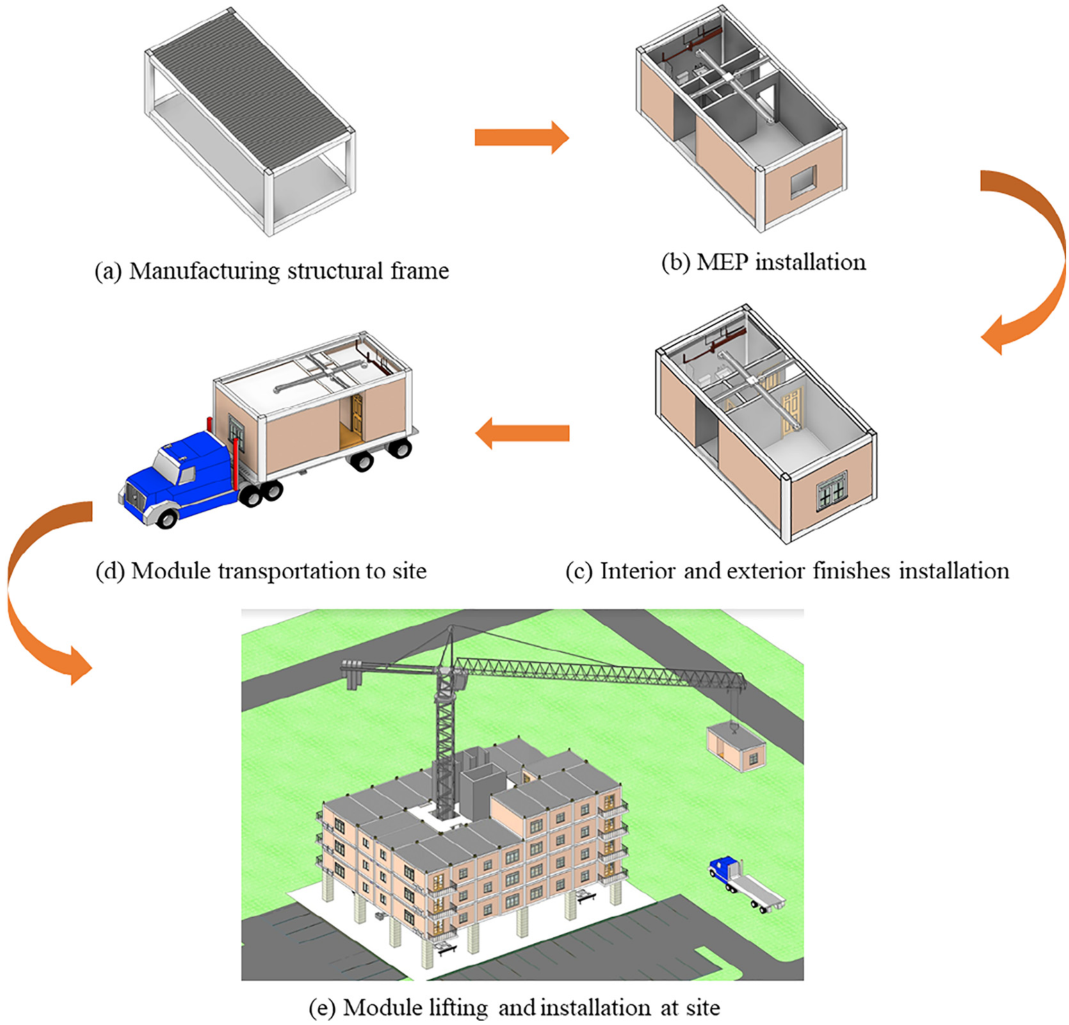


Fig. 4. Modular construction – from manufacturing to site installation.

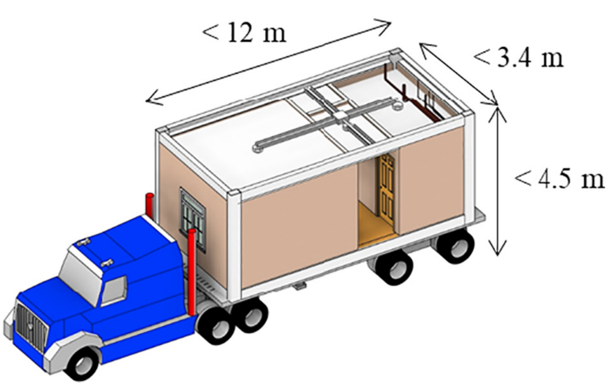


Fig. 5. Module size limit due to transportation truck.

Fig. 6. Tower crane for module lifting [16].

This paper focuses on corner supported modular system, as shown in Fig. 3, because of its high potential in improving construction productivity and higher performance to weight ratio [13]. Despite the advantages of modular construction in improving construction productivity and efficiency, its existing applications have faced several limitations. Firstly, logistics for module transportation from factory to site affects the maximum size and weight of each module design, which in turn influences the number of modules to complete the layout design [11,14]. The size of a typical modular unit should be kept within the land and transport regulatory without requiring traffic police escort. For instance, traffic rules on road transportation require that the width and length of the module should be less than 3.4 m and 12 m respectively, while the maximum height of the module is limited to 4.5 m from the road surface, as shown in Fig. 5, to avoid clashing with overhead bridges [15].

Furthermore, the lifting limit of tower cranes, as shown in Fig. 6, also constrains the weight of a modular unit. Most commonly used tower cranes in building projects have lifting capacity less than 20 t. The cost of the tower crane will increase by up to 60% when its lifting

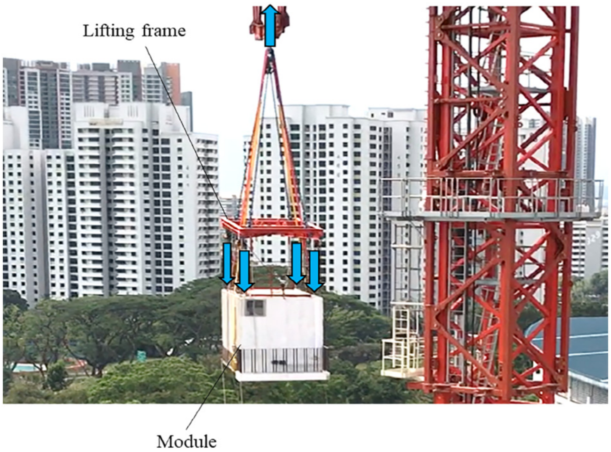


Fig. 7. Lifting frame used during module placement.

requirement exceeds 20 t. Furthermore, the module is attached to a lifting frame and lifted by the tower crane in order to stabilize the module and minimize horizontal forces acting onto the ceiling beams as shown in Fig. 7 [11]. Therefore, hoist weight and module size for transportation are the main restriction in modular design and construction.

Reduction of construction depth and increasing the headroom of module is desirable for building design. Fig. 8 illustrates the difference between elevation view of a conventional building and a modular building. Unlike conventional buildings where single beam supports both the ceiling of the lower story and the floor of upper story, modular structure consists of separate units that are stacked together. Therefore, each module consists of a ceiling beam that supports only the MEP services and floor beam that supports the dead and imposed loads. When the modules are stacked vertically, there are two beams between the upper and lower storeys with a small gap, thus taking up extra vertical space as compared to conventional building. If the required depth of floor beam is larger due to long span or higher design imposed load, construction depth will increase and headroom will be sacrificed even more.

Modules in steel building are connected via beams and columns as shown in Fig. 9. As for conventional steel frame structures, joints in steel modular buildings can be classified as corner joints, perimeter joints, and internal joints. Different joints have different inter-module connection details and thus have different structural performances and loading conditions. Specifically for PPVC modules which consist of six-sided panels and complete with floor and ceiling finishes and MEP, it is preferable that the modules are jointed externally (i.e. outside the module) to minimize on-site work for interior finishes touch up [17]. Furthermore, it is more economical to develop rigid connections between adjacent modules. The rigidly-connected modules can act as an integrated frame structure to resist lateral loads and reduce the reliance on lateral load resisting system. However, it is not efficient to create fully rigid connections using site welding due to space constraint and it reduces the speed and efficiency of modular construction. Therefore, novel modular joint design is needed to achieve fast and easy installation of the modules.

Nonetheless, due to the increased number of connections, there are uncertainties in continuity of the structural components that has significant impact on the overall stability and sway behaviour of the building. Resistance to horizontal and accidental loads becomes increasingly important with the scale of the building [10]. If the modules are connected at the corner joints only, the floor slab of each module acts as a discrete rigid diaphragm and relies on inter-module connection to transfer the lateral loads to the lateral bracing system. It is questionable whether discrete floor diaphragms can provide sufficient lateral resistance as compared to conventional construction methods, in which the entire floor slab acts as a continuous rigid diaphragm [18]. Nonetheless, to connect all the modular slabs together in modular building, additional overlapping rebars and site grouting are needed as shown in Fig. 10. This may reduce the construction speed and require site labour for laying of rebars and site grouting.

Moreover, the geometric and positioning tolerances might result in additional eccentricities loads on the structural components in the modules, as illustrated in Figs. 11 and 12 [4,10,15]. It is reported that the geometric and positioning tolerance of modular building of 10 storeys is approximately $h/350$, which is 60% higher than the tolerance for conventional building that considers the positioning tolerance only [4]. For the purpose of analysis, a notional horizontal force of 1%, which is higher than 0.5% for conventional steel frame building, was proposed for storey up to 12 storeys [4]. Hence, global modelling of modular high-rise building with appropriate joint model and structural design consideration is critical in order to ensure the analysis is able to capture the global behaviour and to ensure its lateral stability.

The control of combined geometric and positional deviations is important in the construction of high-rise modular building. It is recommended that the maximum deviation should not exceed 40 mm relative to the ground datum. This also implies that the reinforced concrete core walls or any laterally bracing systems should be constructed to similar accuracy to avoid unacceptable gap among the modules, causing subsequent installation problems on site.

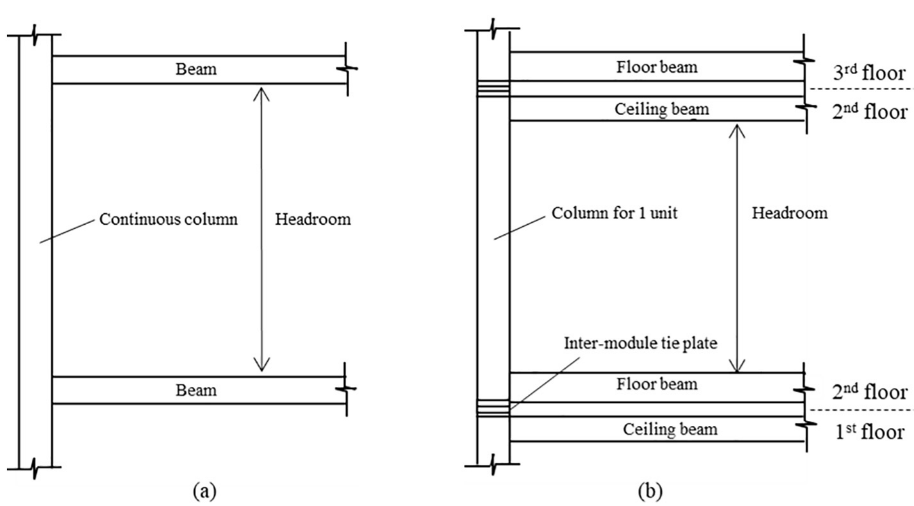


Fig. 8. Elevation view of (a) conventional building and (b) modular building.

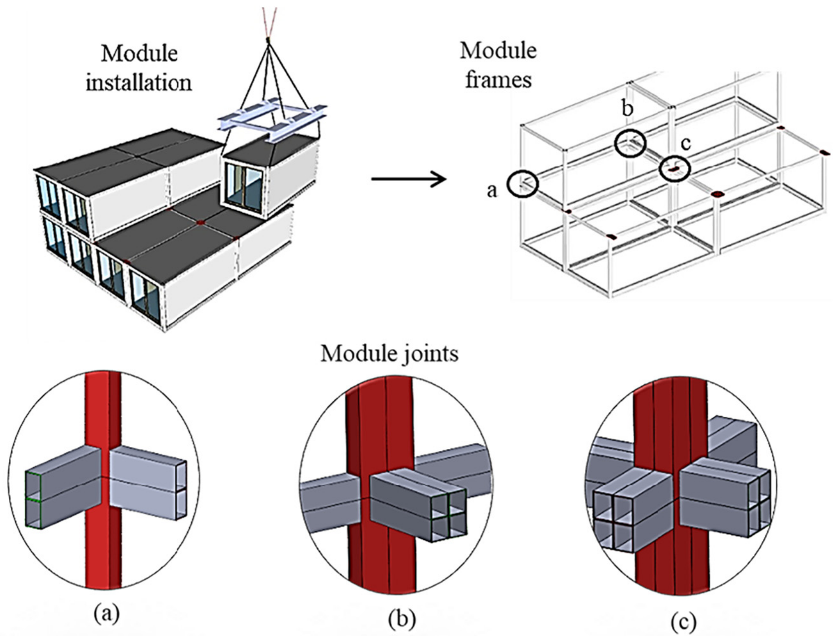
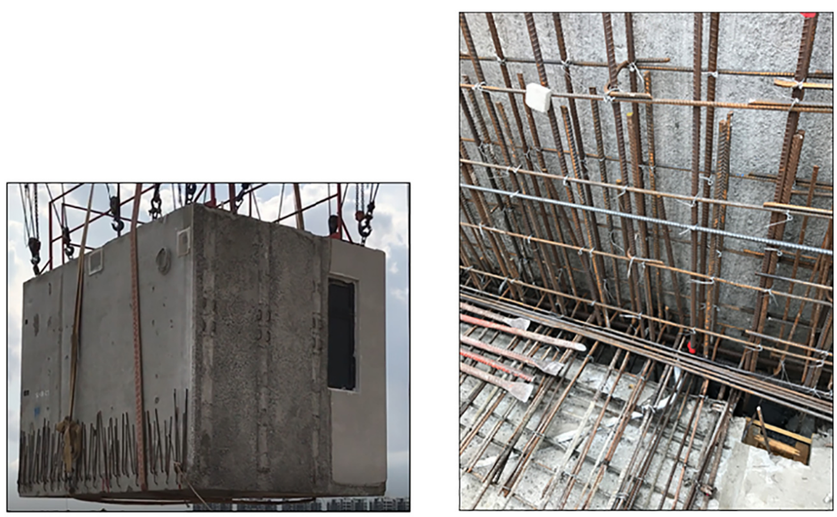


Fig. 9. Modules connected at different joints (a) corner joint with 2 columns and 4 beams; (b) external joint with 4 columns and 8 beams; (c) internal joint with 8 columns and 16 beams.



(a) Modules come with rebars that are bent upwards in factory.

(b) Extensive rebars to tie the module with cast in-situ slab.

Fig. 10. Extensive rebar and on-site grouting needed to tie slabs from all modules to form continuous diaphragm.

In current practice, the productivity and efficiency of modular construction are not yet fully maximized because there is still much labour work involved in the factory as well as at construction site. This is because the initial investment cost in automation technologies is high and there is a lack of skilled labour in construction. The manufacturing of modular units sometimes still involves conventional panelized casting, followed by assembly of panels into modular unit. This causes error in verticality and horizontality of the module (see Fig. 11) that might lead to uneven surface at the gap between two modules and subsequently lead to water tightness problem.

On the other hand, due to lack of automated machines at the construction site, longer time is required to adjust the lifting chains such that the module is balanced before assembly. Poor design of lifting frame leads to unbalanced module as shown in Fig. 13(a) during lifting which may cause damage of internal finishes especially in PPVC whereby the modules are completed with internal finishes. To ensure balanced lifting, multiply pulleys and lifting chains are often needed as depicted in Fig. 13(b), and all these chains are often adjusted manually at site further slowing down the speed of construction. In current practice, the locating of module during assembly is still done manually as displayed in Fig. 13(c). Accuracy positioning and installation of module is crucial to minimize the accumulative error among modules as shown in Fig. 12.

3. Methods to improve efficiency of modular construction

As discussed in Section 2, there are many challenges in high-rise modular construction because its structural form is relatively novel that

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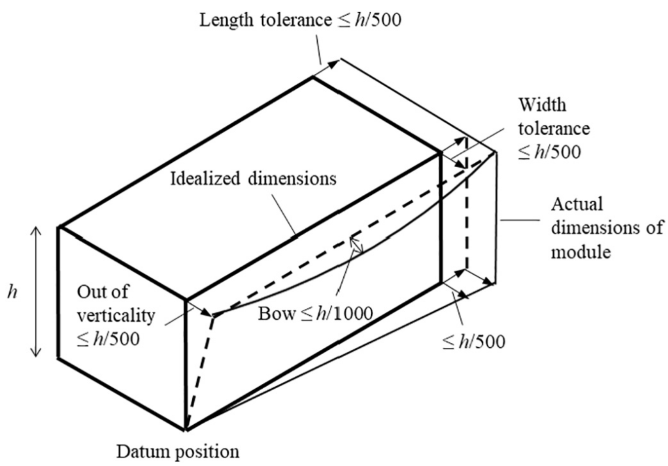


Fig. 11. Geometric tolerance of single modules during manufacturing [11].

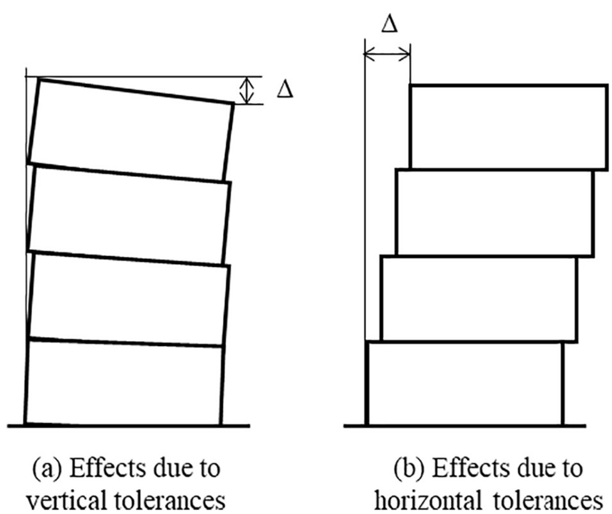


Fig. 12. Positioning tolerances of modules causes accumulative error Δ during installation [11].

is different from conventional building. This section proposes solutions to overcome the current limitations of modular construction with the aim of maximizing the construction efficiency and productivity.

3.1. Composite lightweight modular unit

Since the weight and size of modules are constrained by the transportation and lifting requirements, a composite lightweight modular system is proposed as shown in Fig. 14. Fig. 15 shows the weight distribution in a steel modular unit. As can be seen, the weight of the floor and partition walls can be potentially reduced as they are the two elements of heavier weight in a module. Therefore, structural lightweight concrete can be used in the slab to reduce the weight of a modules by up to 40%. It is also reported that lightweight aggregate concrete is cost-effective and is able to provide good thermal insulation and fire resistance. Additionally, ultra-lightweight partition walls using foamed concrete can be incorporated in the modular system because they are non-structural but can provide good acoustic and thermal insulation [20].

Furthermore, as discussed in Section 2, headroom is also another important aspect in modular building. Composite beam design can be applied by installing shear studs so that composite action can be achieved between steel beam section and concrete slab as shown in Fig. 16(b). Design calculation has been conducted on the beam and slab systems shown in Fig. 16 for residential building with different module spans and their structural depths and steel weights comparisons are demonstrated in Fig. 17. As can be seen, the available headroom in the modules can be increased by 20% to 30% as compared to a pure steel beam design, which is demonstrated in Fig. 16(a). Slim floor beam, as shown in Fig. 16(c), can be introduced into the system to further increase the available headroom by reducing the structural depth by 50 to 75 mm as compared to conventional composite beam with slab on top of the steel beam as shown in Fig. 17(a) [21,22]. Moreover, slim floor system is suitable for prefabricated module because the steel deck can be eliminated as reusable mould can be used for slab casting.

Using pure steel columns in modular high-rise building may cause the column size to be larger or thicker steel section, and thus lead to higher costs and less usable space. For example, for the 32-story braced steel modular systems (B2 Tower) in New York, column sizes were kept to be 150 mm × 150 mm but the thickness of steel was up to 38 mm [23]. Variations of column sizes along the height of modular buildings could lead to difficulties in inter-module connections. To reduce the hoisting weight and maintain the column size, composite design of columns such as rectangular concrete-filled tubular column can be implemented in proposed modular unit as demonstrated in Fig. 14. High strength concrete can be used to infill the steel tubular column to reduce the column size as well as maintaining the column size throughout the entire building for the ease of connection. Moreover, due to weight of concrete cast-in situ is not included in hoisting weight and thus, by separating the infill concrete weight and steel weight, further reduction on hoisting weight can be achieved.

3.2. Long span modular unit

With the aim to expand the applications of modular construction and fully maximize its advantages, a long span modular unit with beam span up to 12 m is proposed. The proposed long span module can increase construction speed by reducing the number of modules and inter-module connections. At the same time, implementation of long span modules allows for larger open space and more flexible floor arrangement as shown in Fig. 18. The proposed long-span modular unit can expand the applications of modular construction from residential and commercial buildings to industrial buildings, whereby large column-free space and higher design imposed loads (5 kN/m^2 to 20 kN/m^2) are needed.

Due to increased floor mass and longer span lengths, the beam deflection and vibration have become an area of concern. As can be seen in Fig. 17(a), for a span of 12 m with typical residential design imposed load of 1.5 kN/m^2, a total structural depth d of up to 600 mm is needed if composite design is not considered. As a result, the increased depth of floor beam will take up more vertical space, so either the available headroom within the modules has to be reduced, or the storey height has to be increased. However, it is shown in Fig. 17(b) that introducing slim floor beam may not contribute significantly to steel weight reduction particularly for module span below 9 m, as compared to conventional composite beam due to larger beam size required in slim floor design. Therefore, slim floor system is more beneficial to be adopted for module span of 9 m and above such that the steel usage is optimized while the available headroom is larger as compared to conventional beam system.

The lateral stability of the structure under horizontal loads such as wind load and equivalent horizontal forces (EHF) may be undermined due to the reduced flexural stiffness of longer-span beams. Moreover, hoist weight of long span modular units will be higher. These issues can be resolved by implementing the composite lightweight modular unit as shown in Fig. 14, whereby the lightweight concrete slab and lightweight partition walls aim for weight reduction while composite slim floor design helps to increase the available headroom in a module.

(a) Unbalanced module due to poor lifting frame design [19].

(b) Balanced lifting with multiple pulleys and chains [16].

(c) Positioning the module at the desired location.

Fig. 13. Problems during module lifting and installation.

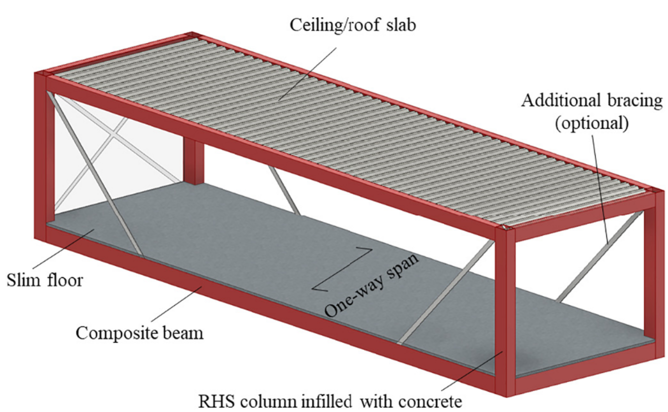


Fig. 14. Proposed composite lightweight modular unit.

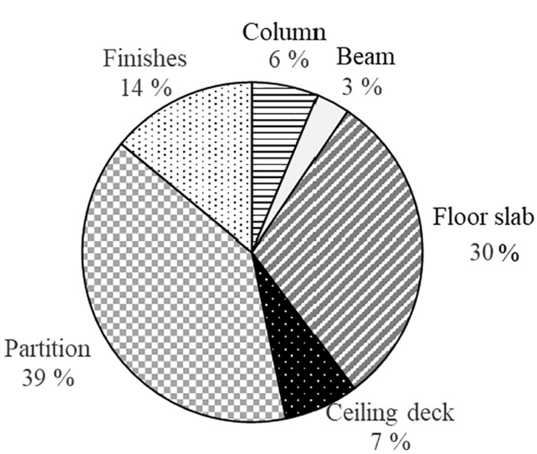


Fig. 15. Weight distribution in a steel modular unit.

3.3. Fast-installed joining techniques

Inter-module connection design in modular construction aims for fast and easy installation yet able to provide sufficient stiffness and resistance. As shown in Fig. 14, rigid welded beam-to-column joints are provided to ensure the modular framework is rigid and robust on its own [24]. The welding of beams and columns can be done in the factory. The module is jointed with the adjacent modules at the corners via beams and columns, as shown in Fig. 9. Many researchers have proposed different types of joints for modular construction, for instances, beam-beam connection and column-column connection using bolts and plates [17]. Beam-beam connection joins the floor beams of the upper module and ceiling beams of the lower module and can be achieved using welding or bolting.

As mentioned in Section 2, welded connection is not preferred on site for inter-module connection as it required highly skilled labour to work in limited space and it is often subject to time-consuming inspection after welding. Thus, connections with different bolting techniques have been proposed as shown in Fig. 19. Past studies show that these connections can be designed to be ductile and strong enough to resist seismic loadings in steel modular system [25–27]. Some researchers commented that this type of connection could result in rigid joints that rendered the modular structure to be just like normal braced frame structure [26] whereas others reported that this joint design can be conservatively assumed as pin joints in global frame modelling [28–31].

Nonetheless, it might not be conservative to assume pin connection for the design of the joints as less forces will be attracted to the joint including the beam-column welded joints [32]. Pin connection assumption could also lead to false effective length of columns and thus overestimates the column capacities in unbraced frames whereas it is a conservative assumption in braced frames [33]. Conversely, it is shown that 'short' segments such as tendon or plug-in device that are meant to provide continuity between columns from upper and lower modules can be added in bolted beam-beam connections as shown in Fig. 19(d) and (e) [25,34]. It is reported that increasing the length and thickness of

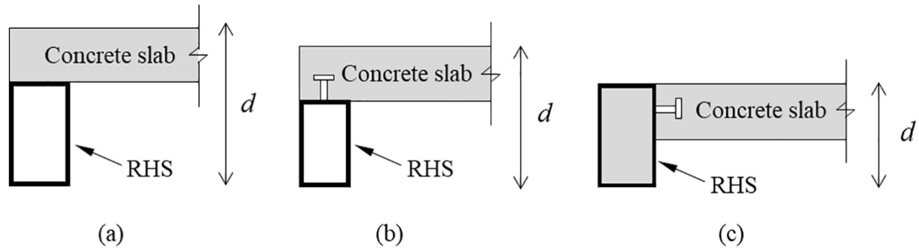


Fig. 16. Structural depth *d* of (a) steel beam (non-composite), (b) conventional composite beam and (b) slim floor concrete filled composite beam.

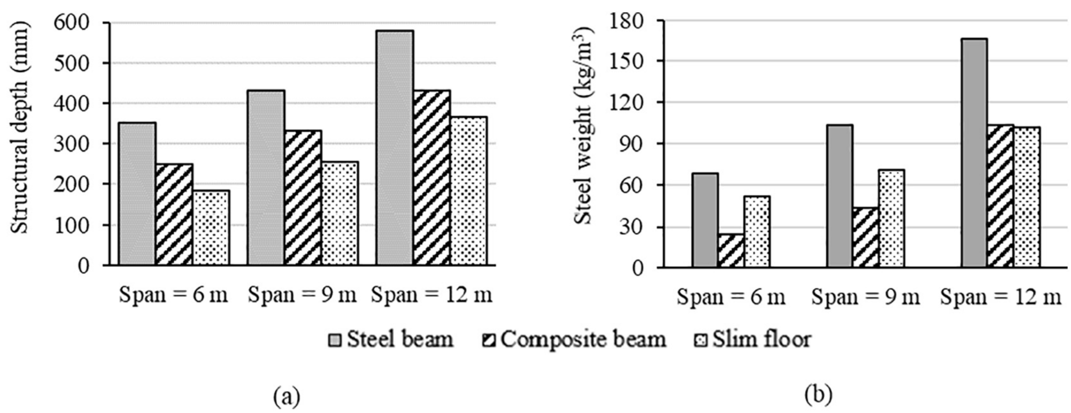


Fig. 17. Comparison among different slab and beam systems (a) structural depth, and (b) steel weight with module spans of 6 m, 9 m, and 12 m for residential building design.

these types of 'short' segment may reduce the effective buckling length of the columns in the module by about 10% to 40% [34].

Nonetheless, bolted connections require more stringent tolerance in fabrication. Large number of bolts usually leads to delay in bolting on site. In addition, to perform bolted connections, entering the pre-finished modules and access holes on walls, floors or ceilings are necessary at every corner of the modules. This will cause potential damages to internal finishes and costly rework on site. While allowing larger tolerance for bolted connection may ensure easier installation, it is not desirable for lateral stability of high-rise modular building as it could result in accumulative drift error as depicted in Fig. 12. Moreover, in modern practices, 100% wall finishes are required in modular construction and thus openings for bolting access is not desirable [6]. Therefore, bolted beam-beam connection may not be idealized for steel modular system.

To solve the above issues, a new form of joining technique is proposed by connecting the columns of the upper module to the columns of the lower modules, and the connections can be done outside the modules [17,36]. Fig. 20(a) shows column-column connection that utilizes vertical rods to connect the columns vertically while using shear key and horizontal tie plate to connect the adjacent modules horizontally. In this connection, the vertical tying between upper and lower modules are done by the vertical rod to resist tensile forces while the columns resist compression force by bearing. The shear forces between upper and lower columns are transferred by the shear key bearing onto the base plate which is welded at the bottom of column of the upper module.

Conversely, for horizontal tying between adjacent modules, shear key and horizontal tie plate are designed to transfer the lateral forces to LFRS. This proposed connection is weak in providing rotation stiffness between upper and lower modules as only the vertical rod is providing the vertical continuity and hence the rotational stiffness may be assumed to be negligible. A semi-rigid model of this connection is proposed as shown in Fig. 21 in order to capture the mechanical behaviour of this connection and be used in global modelling of modular building. This connection is suitable for both pure steel rectangular hollow section and concrete filled tubular columns. Likewise, for connection shown in Fig. 20(b), four strands inside the rectangular concrete filled tube columns are prestressed as it can develop larger rotational stiffness to prevent columns from opening up under extreme lateral loads such as seismic loading [36].

Nonetheless, it should be noted that due to increased number of stacked modules in high-rise buildings, the accumulative tolerance error in successive module placements may potentially become larger [37]. Therefore, the inter-module connection may allow for adjustment of misalignments within a specific range of tolerances [37]. The connection may be designed with alignment guidance during installation of module to minimize the out-of-plumpness. For instance, referring to column-column connection displayed in Fig. 20(a), other than providing shear resistance, shear key helps in aligning the column of the upper module as well as the adjacent modules. A base plate, which is welded at the bottom of column from upper module, helps in the alignment of module placement by fitting with the shear key. Whereas the tie plate helps in positioning the adjacent modules by fitting with the shear keys from other modules.

A recommended tolerance of 2 mm gap is proposed between the shear key and base plate of column above as well as tie plate is considered for the ease of installation as shown in Fig. 22. With the tolerance control in connection design, the maximum positioning error is approximately 20 to 30 mm for 10-storey building, which is lower than the value of 40 mm proposed by Lawson & Richards [4]. However, adding this tolerance might cause the shear key to slip through the gap Δ as depicted in Fig. 22, before engaging with tie plate and base plate from column above. The potential slip of the connection system can be counter-balanced by the frictional force which is relatively significant due to the clamping forces from the column under service loads.

3.4. Lateral stability and robustness of modular high-rise building

Proper modelling of modular high-rise buildings is important to capture global sway behaviour and ensure the stability of the building under various load combinations and extreme load scenarios such as

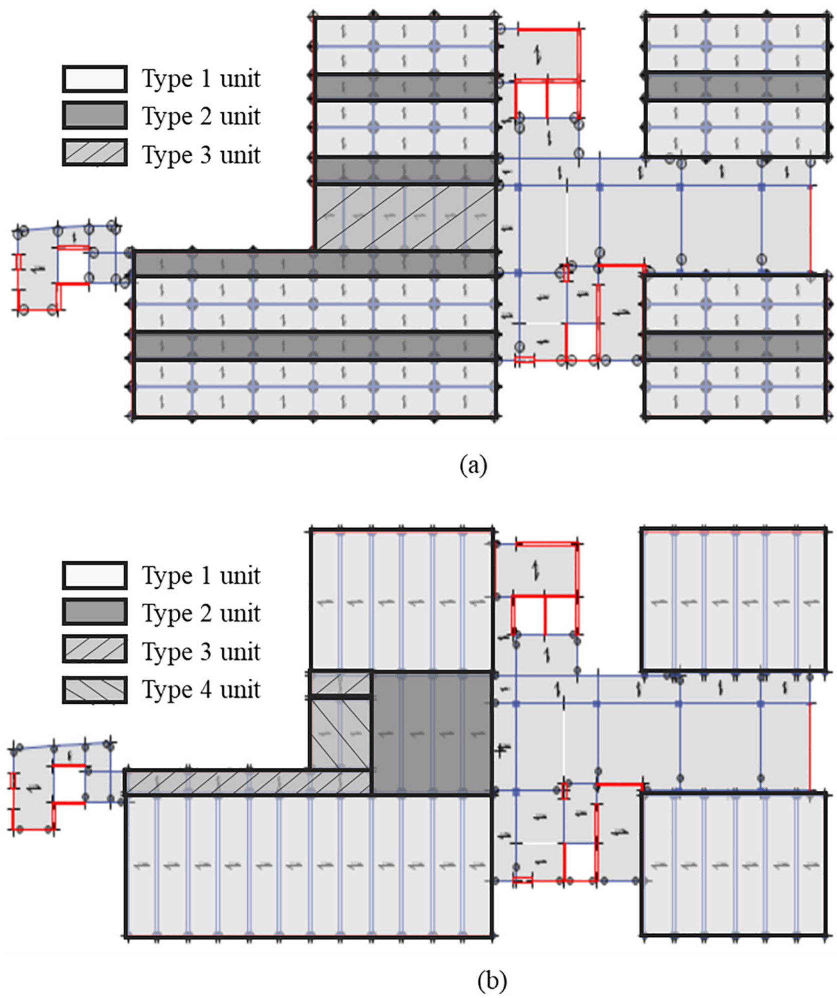


Fig. 18. Comparison of module arrangement for (a) short span (beam span of 6 m) and (b) long span module design (beam span of 12 m).

accidental and seismic loadings. Fig. 23 shows a 40-storey residential modular building that was modelled and studied using the proposed semi-rigid joint model (as shown in Fig. 21). Each module consists of ceiling and floor levels as shown in Fig. 23(b) and (c).

As mentioned in Section 2, an equivalent horizontal force (EHF) of 1% the design gravity loads was proposed because of the geometric and positional error of vertical stacking of modules up to 12 storeys with inter-module connection to be designed as fully rigid [4,26,38]. However, for more than 10 storeys, a lateral force resisting system (LFRS) such as core wall or bracing frame should be incorporated [11,39]. Hence, an EHF of 0.5% recommended by EN 1993-1-1 was used because module alignment can be adjusted at the site along with the core wall [40].

Due to the discontinuity of the structural components among modules, the column-column connection is modelled as pin, and the modules are designed to resist the gravity loads only whereas the core wall resists all the lateral loads. This is due to high core wall utilization ratio of 0.95 which is defined as ratio of base shear taken by core wall over that of the total base shear the building. The assumption of pin-ended column-column connection is safe for non-sway modular building and the horizontal tie plate is assumed to be rigidly connected to the columns [41]. Discrete floor diaphragms can be assigned in each module at floor level as demonstrated in Fig. 24(c) as the modules are connected at the corner joints only. The results show that the building is laterally stable if the inter-module connection is designed properly to transfer the horizontal load via axial and shear forces. The design of floor slab in each module needs to be stiff enough such that each of them can act as a rigid plate [42].

Furthermore, inter-module connections must be able to resist extreme loads due to accidental removal of one module [43]. However, it is unreasonable to assume that the entire module will be removed under an accidental event. Therefore, instead of removing module as suggested by Lawson et al. [43], a robustness analysis was conducted under corner column removal scenario using nonlinear static analysis for the 15-storey building (with similar layout shown in Fig. 23). Fig. 24 shows the load displacement curves at the point of column loss comparing the conventional building with modular building. It is concluded that the progressive collapse resistance of a modular building with modules connected at corner joints can achieve the safety requirement compared to conventional building with equivalent amount of materials [44], although the column vertical deflection at the accidental design load level is 14% higher than that of the conventional building. The tie plates served as critical components to redistribute the gravity loads to adjacent modules due to the column removal.

4. Recommendations for future research

The successful modular construction projects and research show promising potential in improving construction productivity, efficiency and safety, reducing manpower, and generating less construction waste. Nonetheless, there are still many areas require further improvements and research in order to fully maximize the advantages of the modular construction.

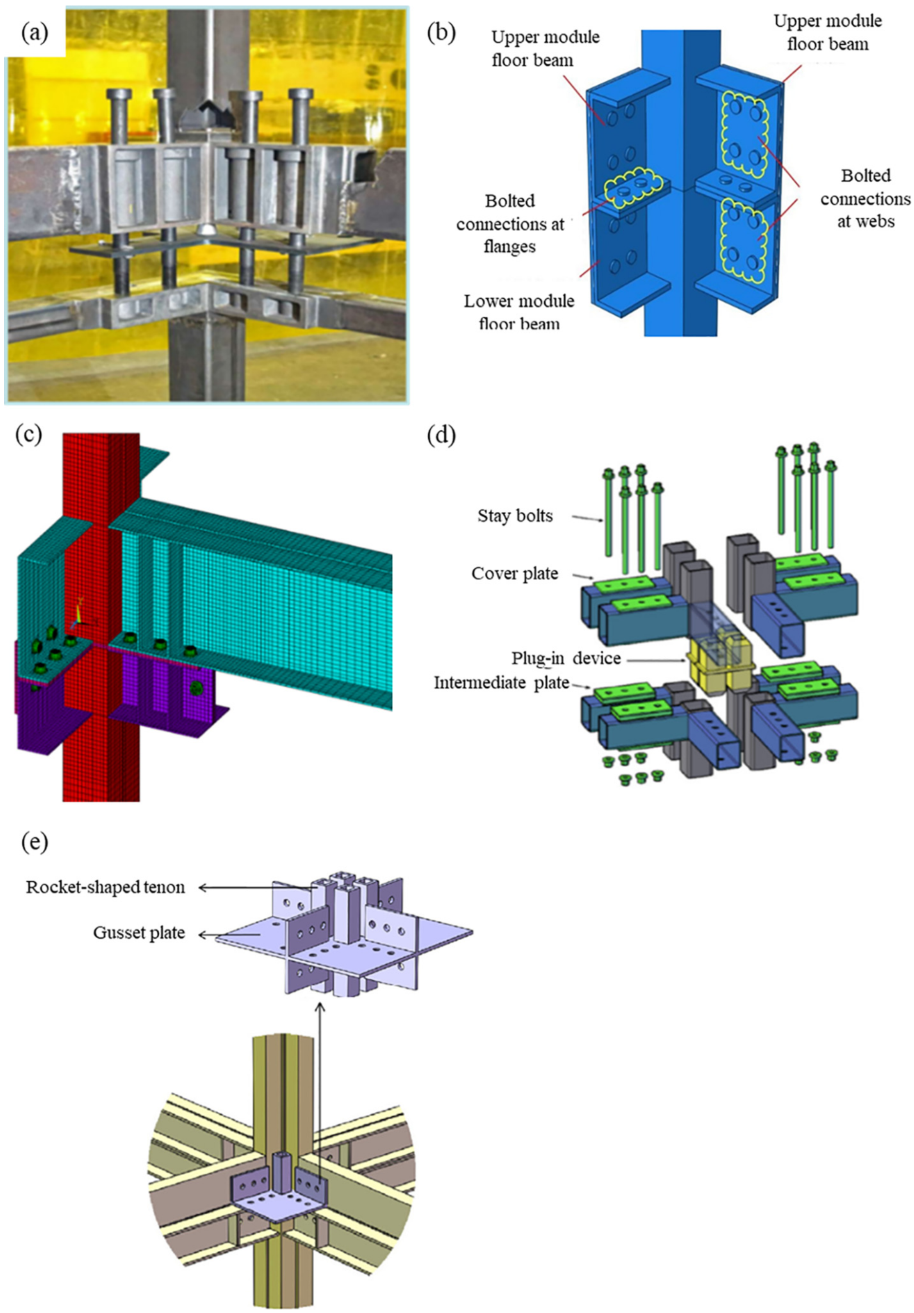


Fig. 19. Typical beam-beam connections: (a) VectorBloc System [35], (b) corner joint [29], (c) perimeter joint [26], (d) and (e) interior joint [25,34].

4.1. Further enhancement for lateral and earthquake resistance

Novel prefabricated and prefinished volumetric structural system can be further developed to speed up on-site assembling with significant labour savings. The system should encourage the standardization of module size and member size while providing a certain degree of flexibility in exterior and interior layout. To do so, the existing corner support modular system, which allows for larger open space and more flexibility in layout, may be added with bracing or integrated with load bearing modular system. This could reduce the reliance on the lateral force resisting system to resist the horizontal load, encourage longer span module design as well as to increase the ratio of off-site fabrication over on-site work in a modular building. In addition, damper system can be adopted into the steel braced modular system to improve the energy absorption capability for seismic design purpose as shown in Fig. 25.

4.2. Fast joining techniques

Moreover, more innovative and fast joining techniques such as snap-fit type of mechanical connector with minimum on-site work can be developed but its effect on global stability, structural integrity and robustness need to be evaluated, especially for high-rise modular buildings. These connectors also need to consider fabrication tolerances for the ease of site installation. Second order analysis of modular high-rise building is necessary to capture the semi-rigid behaviour of connectors to ensure the overall stability of the stacked up modules.

4.3. Development of lightweight and high performance materials

As discussed in Section 3, a composite lightweight modular unit is proposed to solve the existing practical problems in modular construction. Further study can be conducted to develop durable

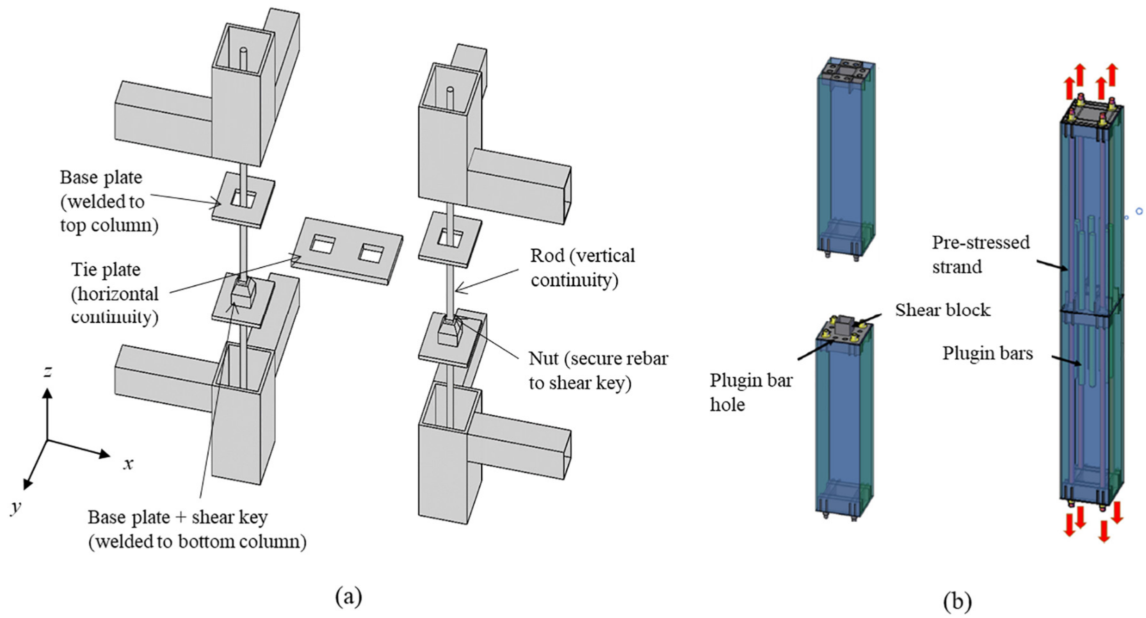


Fig. 20. Column-column connection using (a) vertical rod and (b) pre-stressed strands [36].

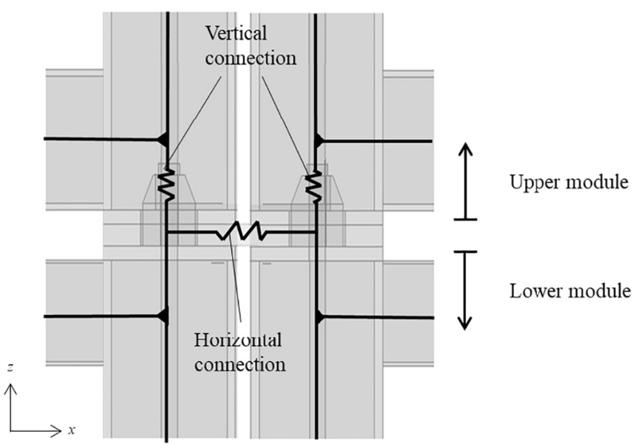


Fig. 21. Proposed semi-rigid joint model.

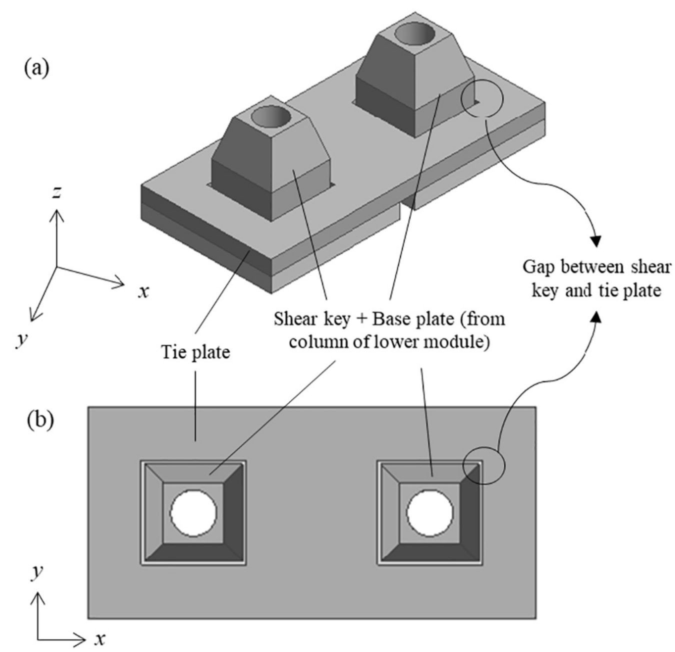


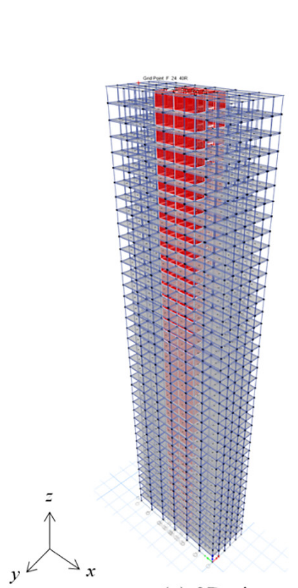
Fig. 22. Tolerance in connection allows for module misalignment adjustment: (a) 3D view and (b) plan view.

lightweight and high strength composite material for both structural and non-structural purposes. Ultra-lightweight materials with low thermal conductivity are suitable for used as internal walls. These materials provide excellent sound and thermal insulation. High strength composite material can be used in columns and structural walls to reduce and standardize the column size throughout the building height. The advancement in these high performance materials can help to produce slimmer and lighter structural and non-structural components in a modular unit, further reducing the hoist weight and module size due to the constraints from transportation and lifting.

These materials can also be developed to be more economical by adding by-product material that promotes sustainability. Nonetheless, the long term durability, material creep and shrinkage of these composite materials shall also be studied to prevent differential settlements between columns and core wall, moisture penetration and water tightness in modular building.

4.4. Fire safety of modular buildings

Fire safety of modular building is an important aspect during the design and construction stages. Local fire safety refers to fire resistance of individual module and global fire safety refers to the prevention of spread of fire from module to module. Building fire safety is achieved by compartmentalization and the use of fire resistant materials to prevent fire spread. Each modular unit is segregated by fire resistant wall and slab to form a separate fire compartment. Therefore, all the structural (i.e. beam, column, and slab) and non-structural (i.e. partition wall) components made of lightweight and high strength composite material need to have adequate fire resistance. Fire stops must be provided at all gaps between modules to prevent fire penetration between the walls and slabs. Means of escape should be considered early in the scheme design in order to ensure that the module design and layout can satisfy these requirements.



Building height (m)	139
Total floor area (m²)	15.8 x 37.5 = 593
PPVC/Total floor area (%)	82

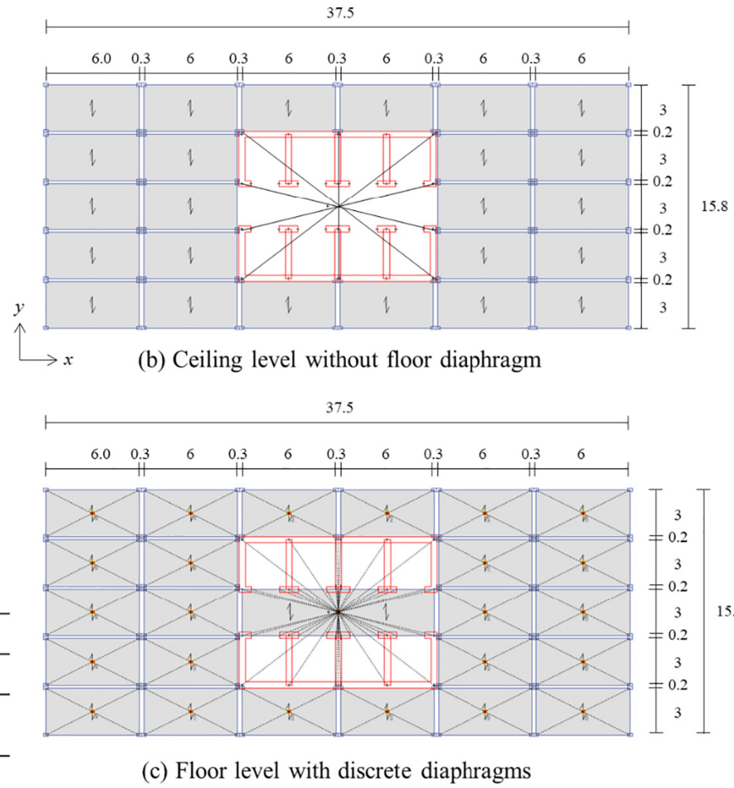


Fig. 23. Global modelling of modular high-rise building.

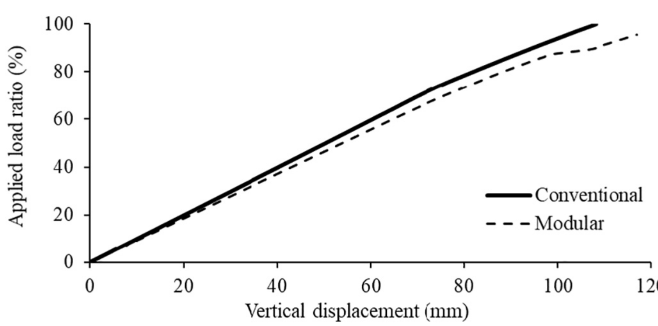


Fig. 24. Comparison of applied load ratio versus displacement curves of conventional building with modular building due to column removal [44].

4.5. Smart and lean construction

Due to high initial cost in investing automation technologies for off-site fabrication of modules and on-site installation of modules, most of the site works are still done manually using labour. Automated lifting and installation method need to be carefully designed to handle new requirements and constraints to ensure safety and high productivity. The effectiveness of this technology can be advanced by integrating with modular component tracking system.

Furthermore, owing to complex logistical requirements and need to increase productivity on site, a logistic supply management system that is lean and optimized to reduce all sources of waste shall be proposed while maintaining an agile response to changes in project requirement. In particular, it ensures that the building materials and structural components are coordinated in economically optimized batch sizes to ensure right product mix for different project configurations. Project

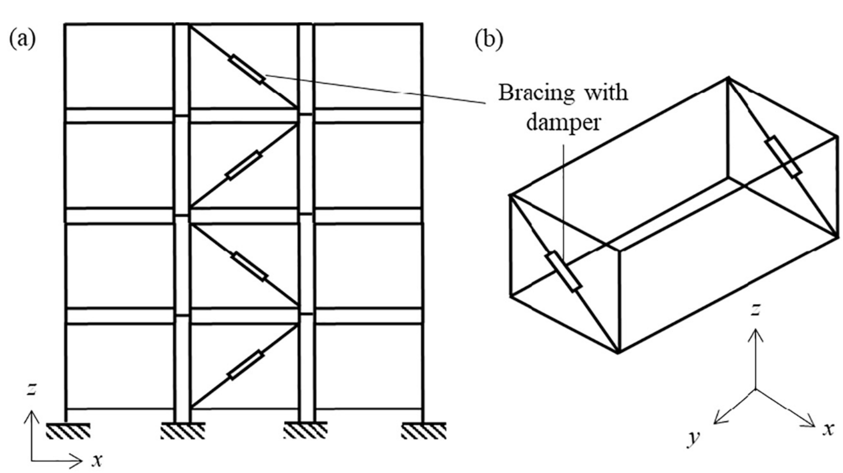


Fig. 25. Adding steel bracing with damper: (a) elevation view of a modular braced frame and (b) 3D view of a module.

schedule drives the procurement, logistic and fabrication schedules to achieve a smooth supply for uninterrupted installation on site. It carefully monitors key constraints so that potential conflicts can be resolved in a timely fashion. This also ensures the resource planning is well coordinated and optimized.

The optimum method to track resources, components and progress efficiently and effectively shall be investigated. A Building Information Model (BIM) for modular construction can be developed to integrate architectural, structural, and MEP design for manufacture and installation. BIM can be integrated with the optimization model and workflow functionalities to provide an effective and competitive project life cycle management from design, through procurement, fabrication and installation. Construction knowledge can be combined into the BIM model to facilitate conceptual design with 5D logistics simulation capabilities so that design can be optimized. It also facilitates information integrity through a single truth source for all project functions.

4.6. Design guide

Lastly, with all the potential areas to be studied, a comprehensive design guide on modular construction can be developed. This design guide should include the design methodology of all the standardized modular connections, composite design of modular unit using lightweight and high strength materials, stability analysis of high-rise modular building, robustness design, modelling of global and local imperfections, compartmentation and fire safety consideration, durability and future maintenance. There is great potential to explore new structural materials including fibre reinforced polymer composites for modular construction. Design guide is currently being developed by the authors with the intention to make prefinished modules to be simple and quick to construct, be robust, lightweight and durable for use in tall buildings.

5. Conclusions

Modular construction shows great potential in improving construction productivity and efficiency. It is believed that modular construction will shape the future construction industry. The followings summarized the key points discussed in this paper to implement modular construction method for high-rise buildings.

1) As the transportation and lifting requirements constraint the weight and size of a module, composite lightweight modular system which incorporates the advantages of both concrete and steel is proposed. Composite beams and concrete-filled tubular columns are proposed for modular design, inheriting the merits of concrete system of being durable, fire-resistant, water tightness and sound proof and carrying the advantages of steel system of being flexible and long span, lightweight, and fast assembly. Lightweight concrete slab and lightweight partition walls are proposed to reduce the weight of a module by up to 50%, leading to lower crane capacity needed. The use of composite column in modular design helps to keep the column size the same throughout the entire building, particularly for high-rise buildings with module repetition and section size standardization.
2) Modular unit comes with double beam system in which the ceiling beam supports MEP services while the floor beam supports the floor loads. This results in lesser available headroom in modular building especially when large beam span is required. Therefore, composite beam design coupled with slim floor system is proposed to reduce structural height and increase the available headroom up to 25% as compared to conventional modular steel design.
3) Long span modular design up to 12 m is proposed to reduce the number of columns for up to 60%, allowing for more open space and lesser connections needed to be installed. With this, the application of modular construction can be extended from residential and commercial buildings to wider applications such as industrial buildings that require larger open space but higher design floor loads. Nonetheless, the increased of structural depth due to the longer span encourages the novel use of slim floor beam system to reduce the module height. The preliminary studies show that slim floor beam system is efficient for module span from 9 m to 12 m in terms of steel usage as compared to conventional composite beam. The use of lightweight concrete slim floor slab can further reduce the weight of the module.
4) With the increased number of connections in modular building, the design of fast and easy joining techniques is important to improve the speed of construction. The joints must be robust enough to prevent progressive collapse due to column loss scenarios. As the modular building consists of many individual units, it is proposed that the modules can be connected via beams and columns from both upper and lower modules. The beam-to-column connections within a module should be designed as rigid. For fully furnished module, the joints between modules should be connected from outside the modules. Novel joints design that connects the modules via vertical rod and horizontal tie plate are proposed to facilitate such work. It is recommended that the vertical tie rod connection between the upper and lower module should be modelled as pin-connected. Conversely, the horizontal tie plate and the shear key connecting the modules horizontally should be modelled as fix-ended to simulate the fact that the tie plate is rigidly constrained at both ends by the clamping force from the columns.
5) Since the modules are connected at the corners, the floor slab of each module acts as a discrete floor diaphragm to transfer horizontal load to the lateral force resisting system as long as the inter-module connections are robust enough to transfer the horizontal loads without significant deformation. It is recommended that global modelling of modular high-rise building should take into consideration of the semi-rigid joints and discrete floor slab behaviour to capture the load displacement behaviour and to ensure global stability at the ultimate and accident limit states.

Improved understanding of the real behaviour of fast joints opens new ways of integrating safety and buildability in the design and construction of high-rise buildings. This paper provides ideas of composite design to modular construction to improve productivity, safety, reduce cost, manpower and wastage on site. There are still many areas require further improvements such as the use of lightweight, high strength, and durable materials to fully maximize the advantages of the modular construction. The works mentioned in this paper are a step toward this development.

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