Title:	**Breaking The Pre-fabricated Ceiling: Challenging the Limits for Modular High-Rise**
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Breaking The Pre-fabricated Ceiling: Challenging the Limits for Modular High-Rise

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Shonn Mills has over 20 years of experience in the design and management of large building and transport infrastructure projects. His international career features experience with long-span bridges, high-rise buildings and the design of large public buildings including airport terminals, metro stations and stadia. More recently, Shonn has been was involved in the structural engineering of the Pulkovo Airport in St Petersburg, Winner of the 2012 IstructE Structural Engineer Award for Transport Structure. He overcame major challenges namely having to design and develop solid structural support in order to adapt to extreme weather conditions.

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Dave Grove has gained considerable experience over his span of 28 years within the structural engineering sector. He has successfully delivered projects overseas and overcome difficult logistical problems and tight timescales by considering the projects holistically and searching for solutions in design, procurement or construction management. He has experience in engineering buildings in all market sectors including residential, hotels and leisure, defence and education. More recently David has been involved in the creation and development of a core team of engineers and specialists who provide technical due diligence appraisals for funders financing major construction projects in the UK and overseas.

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Matthew Egan founded the company Modularize Ltd to address the emerging market for "Design for Manufacture and Assembly" in modern, manufactured construction projects. He has worked for international projects, rendering his expertise and capabilities, from developing lightweight modular systems to reviewing of existing modular systems for improvements in design and manufacturing processes of buildings. Over the years, Matthew, together with Modularize, has built a global reputation for providing outstanding services to the manufactured construction sector.

Abstract

Design for Manufacturing and Assembly (DfMa) technologies including Prefabricated Pre-finished Volumetric Construction (PPVC) have become a viable and sometimes preferred approach in select building sectors. Still less than 1% of High Rise buildings have been built using DfMa or PPVC technologies with the tallest completed examples of fully modular construction topping out at less than 30 stories.

With cities ever increasing densities, there is a drive to push the boundaries of modular technologies. What are the factors limiting the wider implementation of modular construction as a solution for high rise buildings?

This paper explores the technical, market and procurement challenges which have created in effect a modular ceiling. Also what are the solutions which will enable the next tall building boom to the era of Modular Tall Buildings.

Keywords: Design for Manufacture and Assembly (DfMa), High-rise, Modular, Pre-finished Volumetric Construction (PPVC)

Text Pre-Finished Volumetric Construction

The wider development and construction industry now recognize that the adoption of offsite or modular manufacturing for on-site assembly is a key part of the larger construction productivity agenda. Modular is a broad term used in construction to describe the use of technology that facilitates off-site manufacture. The term can be used to describe simple stick frame systems such as pre-cast concrete or prefabricated bathroom pods and up to including fully prefabricated and pre-finished volumetric constructed (PPVC). This paper focuses on the modular PPVC buildings and their application in tall buildings. (See Figure 1)

Modular PPVC construction can provide many benefits some of which are summarized below (See Figure 2):

- Speed: Adopting a modular approach can lead to shorter construction durations on site which can yield an overall shorter design and construction schedule.
- Quality: PPVC deliveries the majority of the final product from the controlled environment of a factory which yields higher quality.
- Safety: More construction off-site means less time off-site and less individual man-hours working at height.
- Weight: The logistical requirements of PPVC drive the design to be up to 30-40% lighter.
- Sustainable: The better quality provided by Modular manufacture also can provide better thermal performance for a more sustainable end product.
- Reduction in Noise and Waste: More production in the factory yields

Figure 1. Modular technology like PPVC is a viable tall building solution (Source: Ramboll Group)

No	Project	Location	Stories	Use	Notes
1	B2 BKLYN	Brooklyn, USA	32	Residential	Project stopped mid-construction
2	T30 Hotel	Changsha, China	30	Hotel	Completed, erected within 15 days, 9 magnitude earthquake
3	Victoria Hall, Wolverhampton	Wolverhampton, United Kingdom	25	Student Accommodation	Completed
4	SOHO Apartments	Darwin, Australia	29 (21)	Residential/Hotel	Modular constructed on conventional podium
5	Hilton Palacio Del Rio Hotel	San Antonio, Texas	21	Hotel	First four floors built of conventional, reinforced concrete for support facilities
6	Wembley BNCE	Wembley, United Kingdom	19	Hotel	Traditional reinforced concrete up to the podium transfer slab, 12 stories of modules inclu. sloped roof
7	Paragon Development	Brentford, London	17	Student Accommodation	-
8	Nanyang Technical University (NTU) North Hill Hostel	Singapore	13	Student Accommodation	On-going
9	The Crescent, Plymouth	Plymouth, United Kingdom	13	Student Accommodation	-

Table 1. Tall PPVC Buildings (Source: Ramboll Group)

Figure 2. Benefits of adopting PPVC (Source: Ramboll Group)

less waste on-site for another environmental benefit.

- Innovation: Modular design allows the prototyping and testing new technology in the factory which encourages and de-risks early adoption of new technology.

Why Modular High-Rise?

Tall buildings as a typology are inherently modular, where good design practice embraces the concepts of simplicity, standardization, repetition and economy of scale. All of these characteristics align strongly with the modular PPVC approach and benefits described in the previous section. Still less than 1% of tall buildings are constructed using modular technologies and when a developer has chosen to go truly modular (PPVC) the real built examples top out at around 30 stories. Refer to Table 1 and Figure 3 for some examples of the tallest PPVC buildings in the world. (See Table 1)(See Figure 3).

On the surface, modular construction has many clear advantages which seem suited for High Rise Buildings. That said, what are the barriers and challenges that appear to have created a height limit got Modular High Rise?

Challenges to Modular High Rise

The design drivers and constraints for High Rise construction are well understood and documented, and for modular construction, many of these drivers are further complicated. The following section provides a discussion of the key considerations and challenges to Modular High Rise as well as some potential solutions.

Vertical Loads

As with traditional construction the loads for modular construction increase with the height of the building. True volumetric construction utilizes the modules themselves for some or all of the vertical load carrying capacity. The best way to understand the vertical load path for modular construction is to understand the basics load bearing components.

Chassis

PPVC systems are like automobile and rely on a chassis or frame which acts as the skeleton for the other components. The chassis frame, typically 3m x 4m x 6m is integrated with the vertical structure and can also provide part of the lateral force resisting system and can be built out of different materials. (See Figure 4)

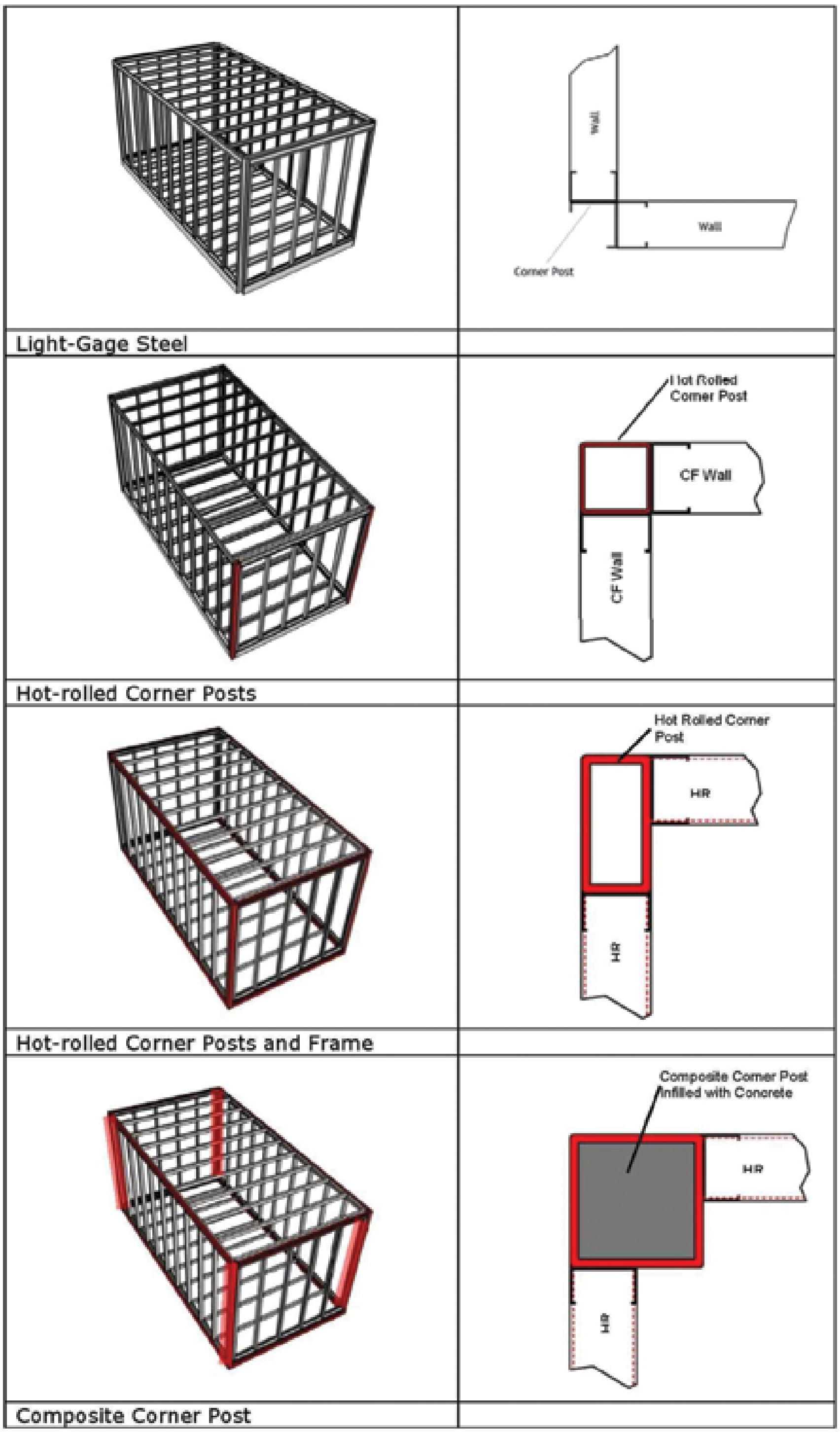


Figure 4. Modular chassis types (Source: Ramboll Group)

Light Gauge Steel

The most common type of chassis in modular construction is cold formed (CF) light-gauge steel (LGS). In this approach the module box is constructed using cold formed C studs at regular spacings and the vertical loads are transferred along the walls. Cold formed section steel modules are typical limited to buildings less than 4 stories due to the relatively low vertical loading capacity.

Hot Rolled Steel

For construction in excess of 4-stories hot rolled structural sections are introduced in to the chassis to increase the modules load carrying capacity. The most common arrangement is a corner post arrangement where the four corners are constructed using structural steel rectangular hollow sections. The corner post approach is applicable for heights up to 13 stories. For more than 13-stories a full structural steel frame consisting of posts and perimeter beams is inserted in the module to provide additional stiffness. This type of chassis has been proposed for up to 30-stories and could theoretically be appropriate for even taller applications.

One of the main challenges for the chassis in a high-rise context is the size of the corner and infill posts which increase with height requiring larger dimensions than the partition wall which affects space planning.

Composite

One potential solution which has been used with some success is a composite steel post solution where the units are installed with hot-rolled hollow section posts which are in-filled with concrete after installation. This can significantly improve the load carrying capacity of the vertical members, although has the disadvantage of introducing a wet trade on-site.

Other Materials

There are a variety of other chassis types which have been proposed or are on the market. These include timber frames systems which are only appropriate for low-rise construction or even fully pre-cast concrete systems which potentially could be suitable for taller applications but currently require a secondary structural frame for support or create considerable challenges for carnage during installation.

Floor Systems

Secondary to the vertical load path is the floor system of the module which contributes the majority of the dead load for each unit. The unit weight can also become a driver for the logistics of delivery and installation.

Light Gauge Steel with Boarding

The most common form of flooring adopted for light gauge steel modules are cold formed floor joists/beams with various types of boarding. The most common options include timber based boards (e.g. plywood OSB), gypsum based boards and cement based boards. While this floor system provides one of the lightest floor plates the disadvantage of this approach is that it does not provide the same solid construction experience.

Light Gauge steel with lightweight screed

To address the lack of "solid feel" in board systems a number of solutions have been developed which consist of cold form joists/beams with a troughed metal deck and various types of lightweight screed such as Lytag, Gvylon and main others. These screed solutions provide the mass necessary to improve the acoustic properties of the floor and enable under floor heating solutions. The weight of this type of floor system is typically 120 to 140 kg/m2 and while heavier than boarded solutions still they provide the solid construction experience similar to a concrete frame construction.

Concrete

At the other end of the spectrum is a fully concrete floor system which can be constructed using pre-cast elements or traditional fresh concrete construction. The weight of this type of floor system is typically between 300 and 360 kg/m2. The overall weight of the concrete solution gives it a real disadvantage for high-rise applications. (See Table 2 and Figure 5)

No	System	Chassis	Floor Construction	Max Height	Lifting Weight[1]
1	Cold-formed Posts	All CF Steel Galvanised	Steel with gypsum board	G+3	5-6 tonnes
2	CF Walls	Double CF Steel	Steel with light weight screed	G+10	6.5-8.0
3	Hot Rolled corner post	Hot rolled Steel corner Posts/ CF Sections for walls and ceiling	Steel with gypsum board	G+12	5.5-6.5 tonnes
			Steel with light weight screed		7.0 - 8.5
4	Full Hot rolled frame	HR Posts and Beams CF Sections infill to walls and ceiling	Steel with gypsum board	G+35	6-7 tonnes
			Steel with light weight screed		7.5 - 9.0
5	Pre-cast Concrete	All sections in precast concrete	Pre cast concrete	G + 40	30-40 tonnes

Table 2. Summary of PPVC Technology (Source: Ramboll Group)

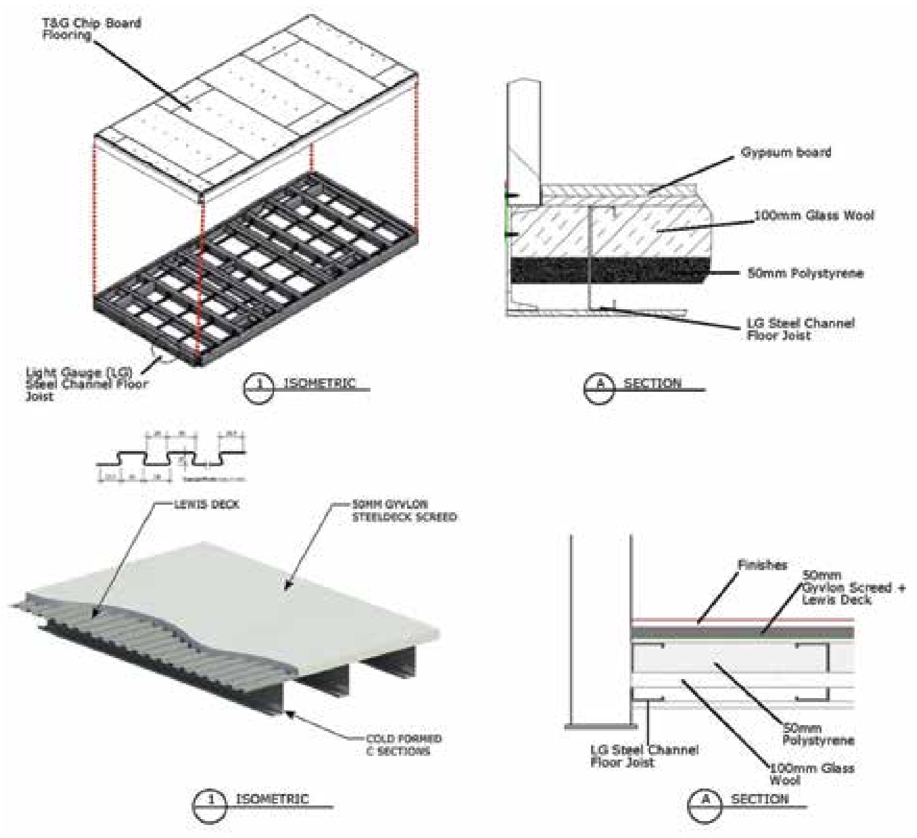


Figure 5. Modular floor systems (Source: Ramboll Group)

Stability

One of the key design drivers for Tall Buildings is the response to lateral loading from wind and seismic forces. This not only includes strength considerations but also wind driven accelerations which should be within acceptable limits for the comfort of occupants. The following section summarizes the most common stability philosophies employed for modular construction.

Self-stable

Modules in multi storey buildings with multiple similar rooms up to about 10 floors are able to be designed as portal frames. The individual modules are designed to resist the vertical load and lateral forces from wind.

Stability Core

Taller modular buildings rely on a central core for their stability. The modules are still designed to resist vertical loading over the full height of the building but not the lateral forces. The core which will accommodate, lifts, stairs and services risers are designed to resist the lateral forces from wind. To enable the lateral forces to be transferred to the core structure the modules have to have additional bracing within the floors and ceilings.

All traditional construction methods in concrete and structural steel can be utilized for cores in modular building but to compliment the offsite construction methods and faster erection of modular buildings pre made core solutions are more desirable. The three main options are;

Core modules

For buildings up to 10 stories modular cores can be used. The lifts and stairs are incorporated in to hot rolled steel framed and braced modules designed to resist the lateral forces from wind. This option has the advantage of being erected at the same time as the rest of the floor and will incorporate similar connection and erection methods as the room modules.

Pre-cast concrete

Another option for the central core is utilizing pre-cast concrete such as twin wall. The twin wall option involves the pouring or insitu concrete between the two wall panels and has the ability to include additional reinforcement across the panel joints enabling this method to more easily resist greater lateral forces. Cast in steel plates or proprietary cast in channels such as Halfen are required to enable the modules to be connected to the concrete.

Steel Composite

Another option for a pre-fabricated core is steel such as "Corefast". This option is similar to twin wall and requires the pouring of insitu concrete and possibly the inclusion of additional reinforcement between the panels. Steel brackets to connect the modules to the core can be welded to the walls.

Connection between the modules and the core structure need careful planning and designing to accommodate the different building tolerances between the core structure and the modules. There is also a need to accommodate elastic shortening of the core and the modules.

1. Based on the 4m x 3m x 6m module.

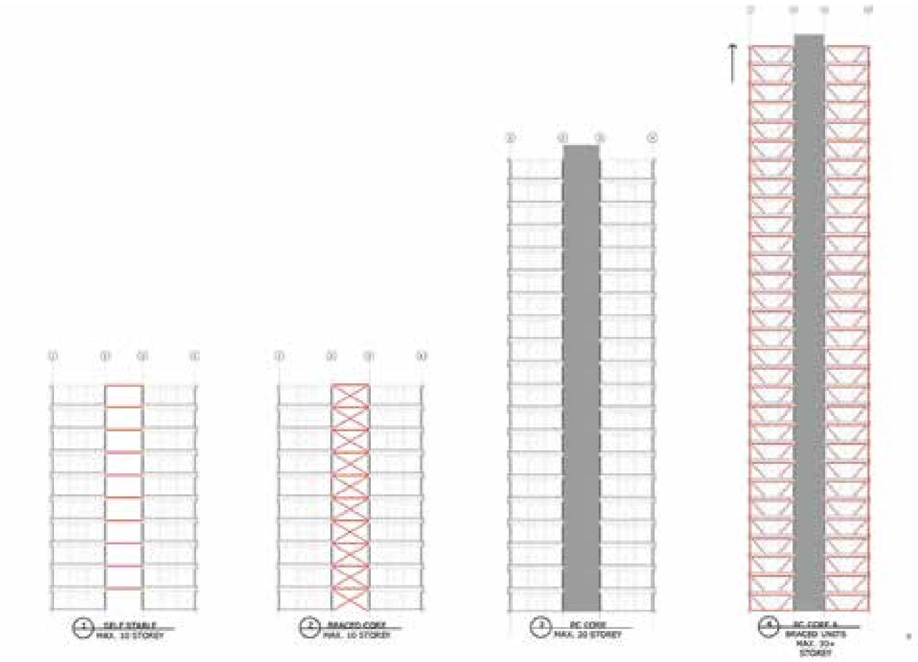


Figure 6A. Modular stability systems

Figure 6B. Modular stability systems

When the building form on plan is elongated and extends away from the core further lateral stability bracing is required. This can be achieved by including in-plane trusses within the corridors and floors of the modules. (See Figures 6A and 6B)

Tolerances

PPVC has the advantage of being manufactured off-site in the factory and this allows for very tight tolerances when compared to traditional construction. Still with today's technology tolerances achieved for each installed unit will be within 5-10mm. This kind of tolerance could lead to significant additional internal forces for high rise construction.

Connections

The load transfer between modules is critical to the overall structural stability and robustness of the completed building. The connections need to be designed to transfer horizontal forces due to wind and extreme or accidental forces due to disproportionate collapse, earthquake using a similar mechanism as traditional construction.

One of the main advantages of PPVC is that they will ideally provide a fully serviced and finished interior. To realize this advantage all of the structural connections should be made external to the unit. The connections are typically made at some or all of the 8 corners of a module. The erection and installation sequence plays a bit role in the design here as some of the potential connection points may not be accessible depending on the location of the unit in the final building. The following summarizes the most common modular connections utilized.

External Plates

The most common type of connection arrangement is horizontal and vertical plates bolted to the external face of the modules. These are typically hot-rolled steel splice plates in various arrangements. Installation of the external face plate is typically done using a mobile working platform which makes them difficult to implement in a tall building.

There are alternative proposals developed by manufacturers for interlocking/locating connections which require no or limited access to complete the connection.
These types of connections have obvious advantages for high rise construction but they need to be designed to accommodate lack of fit/tolerance.

Interlocking

These types of connections generally consist of some type of pin or plug inserted into a recess or socket (male and female type connection). These connections predominately rely on an interference fit or deformation of one of the elements to "wedge" together. These connection types are the nearest solutions to the "Lego brick" and appear to a good solution for high rise modular building where access will be difficult at height.

Cam-Lock/Twist-Lock

Another version of an interlocking connection is the cam-lock/twist-lock which is widely used in shipping containers which have also been used as chassis for modular buildings. This is a positive fixing solution which once fully engaged locks the containers together. However, these still require manual operation of the locking pin from an access platform.

Composite

(See Figure 7) Another potential solution to improve the connectivity of units is steel composite. As described in vertical loading section, this approach utilizes hollow sections as the main vertical structure which are filled with grout and concrete. This forms effectively a reinforced concrete connection at the joints. This approach has real potential for modular high-rise applications but has the disadvantage of introducing a cast-in-place concrete trade into the module installation.

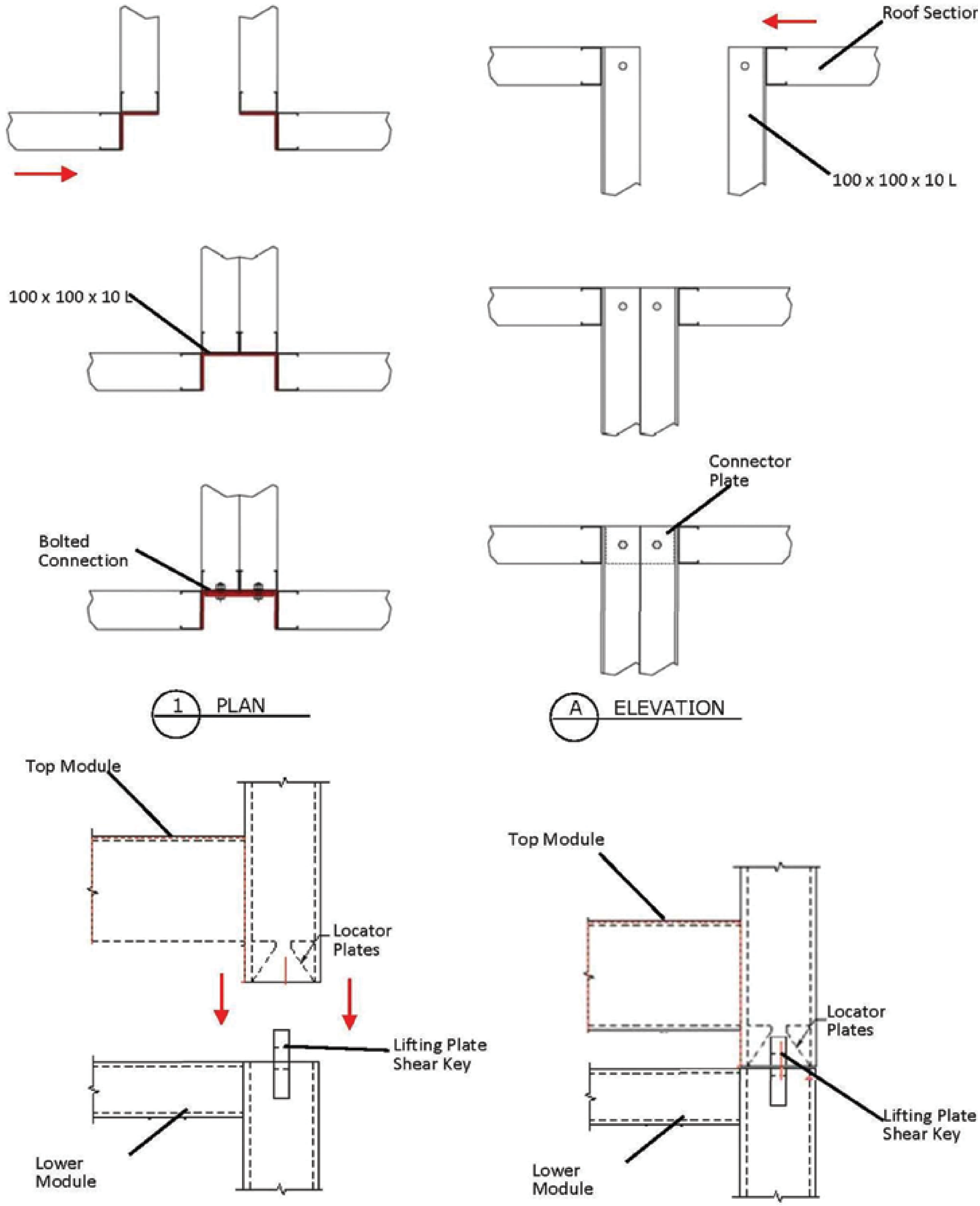


Figure 7. Connections

Figure 9. Building Services (Source: Ramboll Group)

Figure 8. CitizenM Glasgow – mast climbers installing cladding (Source: Ramboll Group)

Figure 10. Aesthetics (Source: Ramboll Group)

Figure 11. Logistics (Source: Ramboll Group)

Life Safety and Fire Protection

Life Safety and Fire protection is a key concern in high rise construction due to the potential for a significant loss of life from a failure of a few elements. This requires a high level of fire protection to the critical structural elements. Current leading modular technologies are largely steel construction to minimize the weight of the units. With Steel construction being one of the leading materials used for modular buildings makes PPVC particularly vulnerable to fire.

The cellular nature of modular buildings means that fire safety has to be considered individually and as a whole building. Safety in the event of fire is achieved in buildings by compartmentalization to prevent fire spread. Individual modules and the building floor or compartment need to achieve the required fire resistance.

Fire resistance of modules is achieved by the introduction of multiple layers of wall boarding such as plasterboard or other types of fir resisting boards. The overall build up is then tested and certified to the duration of fire resistance achieved. There are fully tested and certified light gauge steel wall solutions which achieve 120 minutes fire resistance. In hot rolled framed modules intumescent paint may be adopted in lieu of multiple layers of boards to reduce the increase in construction thicknesses.

The gap between each module both vertically and horizontally also requires sealing to achieve the compartmentalization requirements of the building design.

Cladding, facades

Cladding systems may be pre attached to the module or installed as separate elements on site. In both cases the connection between the modules may be concealed or emphasized as part of the detailing of the cladding. On low rise modular building ground supported cladding solutions such as brickworks are commonly

Figure 12. Manufacturing process (Source: Ramboll Group)

adopted. For higher rise buildings the cladding will normally be supported from each module. (See Figure 8)

Pre installation of the cladding to the modules has similar issues to the seals between each module. The cladding system would have many joints each of which need create a weather tight joint. Tolerances are a further consideration and the alignment of adjacent cladding panels. This is an area requiring more research collaborations with cladding manufactures to develop solutions which will overcome these issues.

Building Services

Modular building services can be a real advantage and time-saver for high-rise construction. Building services located within a module are installed and fully tested in the factory before delivery to site. Final connections to the central services and drainage through the building are made on site. (See Figure 9)

Building Efficiency

Building efficiency or Net to Gross area ratio is one of the primary metrics by which developers measure the potential profitability of a building. As buildings grow taller the demands of structure and building services grow with the height which has a negative effective on the net to gross ratio or building efficiency. Building efficiency is a strong consideration in all high rise buildings. PPVC construction creates a further challenge to building efficiency where in effect there can be two walls between each PPVC unit. (See Figure 10)

Aesthetics

To take advantage of modular construction the architecture must be aligned with the constraints and language of the selected PPVC system. This means in many cases adoption of a massing approach using a combination of rectilinear units which many designers find limiting.

Logistics

The success or failure of a PPVC building project is often decided on the logistics approach. One of the main advantages for PPVC over traditional construction is speed. The on-time delivery and installation of the modular units is dependent on the considerations such as delivery, crane location and laydown area.

Transportation

The national regulations for items transported on roads needs to be considered when designing a modular building. Ideally the size of a single module should be limited to the dimensions allowed without requiring special measures such as police escort. Generally a module width of less than 4.3m should be considered as a sensible maximum. Height is also an issue if the route involves passing below bridges and in general a module height is less than 3 m is sensible if transport is via articulated lorry.

Cranes

Modules are generally lifted from their corners ideally using a lifting frame to avoid introducing inward component forces into the module. Sizing and arrangement of cranes on a site will be dictated by the total lift weight of the module, the reach of the crane. Tower cranes are the most common type used on high rise buildings but with a limit on the maximum weight at the extension of the reach.

Site layout

One key consideration for modular construction is logistic space for the delivery and offloading of modules. It is normal practice to lift directly off the back of the delivery lorry. Therefore deliveries need to be carefully planned and coordinated to avoid congestion outside the site as multiple modules arriving at the same time. In inner city sites which is the norm for high-rise construction, it is common to rent a holding area on the outskirts of the city with sufficient space for a many lorries with modules. Each vehicle is then timed to be called forward to the site while the current module is being installed. (See Figure 11)

Manufacturing and Procurement

Module manufacture is a co-ordinated assembly process with required skilled trades such as steel welding to installation of building services and drywall.
The manufacturing process includes construction of the frame and erecting in the factory. Once the skeleton frame of the module is in place it is then progressed through a number of fit-out stations or cells much like an assembly line. At each stage the module can be finished internally and externally. Work packages such as plumbing, electrical second fix, painting and cladding can all be completed at separate work stations along the manufacturing process. (See Figure 12)

The technology involved in manufacture of modular solutions is generally very accessible. The processes and systems used to integrate different pieces of a modular solution are not more complicated than those used in most production manufacturing. Still the modular building production market is relatively small and there are only a handful of active experienced manufactures and contractors. This limited pool of suppliers makes procurement and supply chain a potential risk to implementation of PPVC. This supply chain limitation can further complicated on a regional basis with most of the suppliers being based in Europe.

Module manufacturers typically act as suppliers of the modular PPVC product to the General Contractor. The nature of modular buildings means that the modular manufacturer is the key supplier to the

Item	Manufacturer	Region	PPVC System	Max Height	Notes
1	Corus Living Solutions	Europe	Cold-Formed/Structural Steel Hybrid	6	-
2	Elements Europe	Europe	Cold-Formed/Structural Steel Hybrid	14	-
3	Caledonian Modular	Europe	Cold-Formed/Structural Steel Hybrid	17	The Paragon Project, London
5	Future Form	Europe	Cold-Formed/Structural Steel Hybrid	17	Victoria Hall Project (West Wing), UK
6	Vision Modular Structures	Europe	Cold-Formed/Structural Steel Hybrid	24	Wembley BNCE, UK
7	Zachary Construction Company	USA	Cold-Formed/Structural Steel Hybrid	16	-
8	Moderna Homes	Asia	Reinforced concrete	13	NTU Housing, Singapore
9	Sembcorp EOSM	Asia	-	-	-
10	UB/Rush	Asia	Cold-Formed/Structural Steel Hybrid	10	Crown Plaza, Singapore

Table 3. Manufacturer Summary (Source: Ramboll Group)

general contractor which creates a strong inter-dependency.

Some of the major manufacturers have researched modular tall buildings or have products which could be applied or adapted for high-rise. Refer to Table 3 for a list of some of the main module manufactures in the market today and their PPVC systems relevant for tall buildings. (See Table 3)

Legislation

The benefits of modular construction have influenced and inspired forward thinking municipalities. One of the best examples of this is the Singapore Government where they have implemented legislation to encourage modular construction to improve productivity and quality in the local construction market.

The Singapore construction industry has historically utilized traditional on-site techniques like reinforced concrete and is dependent on a large migrant labor force. In response to the increasing impact of traditional construction on Singapore's urban areas, the Building Construction Authority (BCA) has created the Construction Productivity Centre which promotes the use of construction technologies to reduce the dependency on labor and save time on site. The Construction Productivity Centre actively promotes the use of modular construction and PPVC providing literature and training to the local market. This initiative extends beyond promotion and includes actual real funding where the government provides grants to encourage contractors to utilize these new technologies in Singapore.

Singapore's dense skyline has long been dominated by High Rise construction. This combined with the new promotion of modular construction makes it the perfect place to implement and test Modular High Rise techniques.

Tall Building Modular Prototype

As part of the research for this paper we developed a prototype modular PPVC tall building. For the building we selected Duxton Plain which is a 50 storey residential buildings constructed by the Singapore Housing Development Board. For this study we utilized the Duxton Plain floor plate and adapted and optimized it for modular construction (See Figure 13).

For the prototype project we utilized a HR and CF steel frame chassis w/composite concrete corner posts to increase the vertical load carrying capacity. The floor plate is a CF steel w/decking and light-weight screed to provide a higher performance. The proposed lateral load resisting system is a hybrid utilizing a conventional concrete core and select modular units fitted with steel bracing in the walls so to provide frame action. To control the lateral load response and ensure the comfort for the eventual occupants the prototype will have an allowance for a slosh damper in the upper stories. The connection

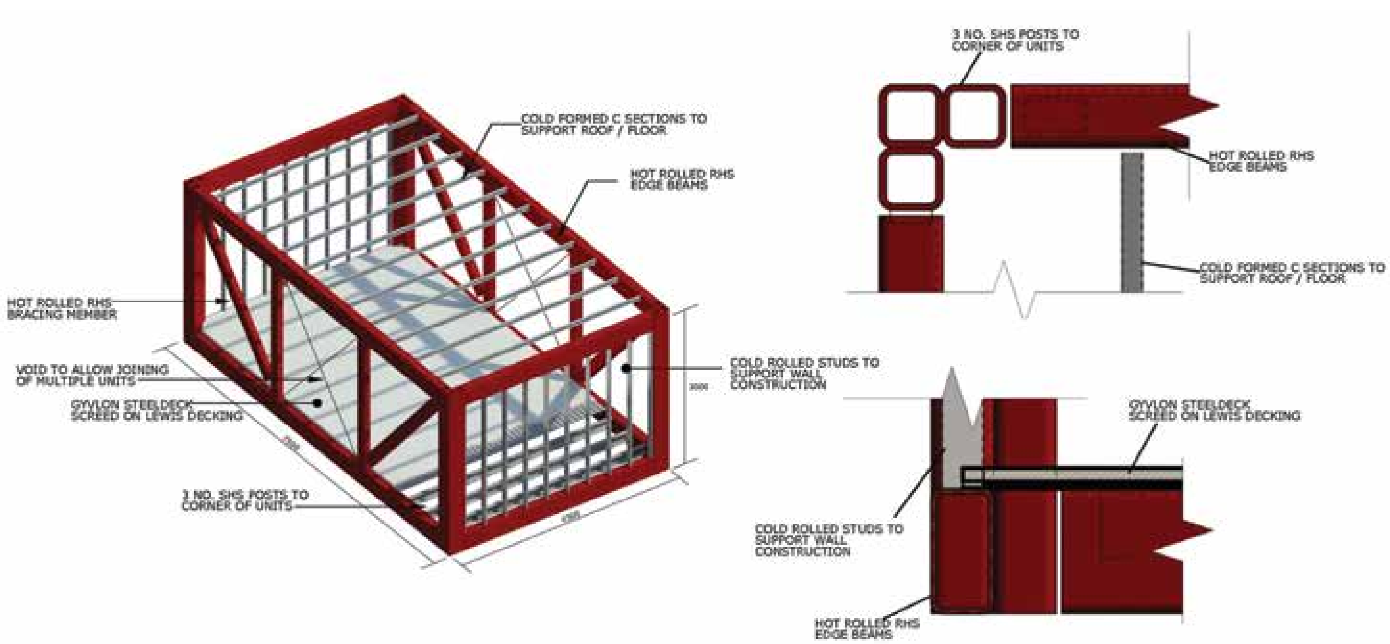
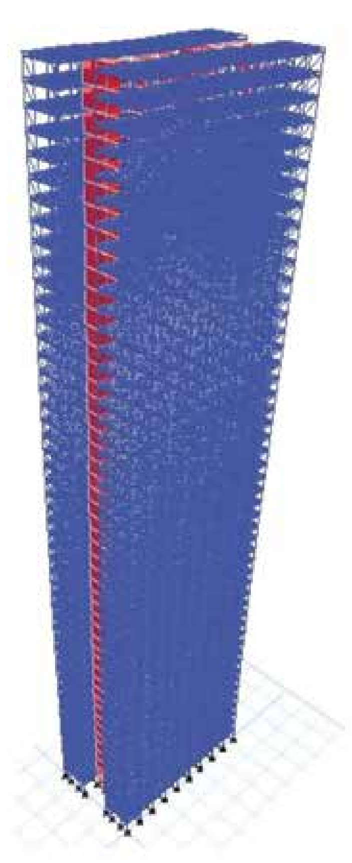


Figure 13. Prototype unit (Source: Ramboll Group)



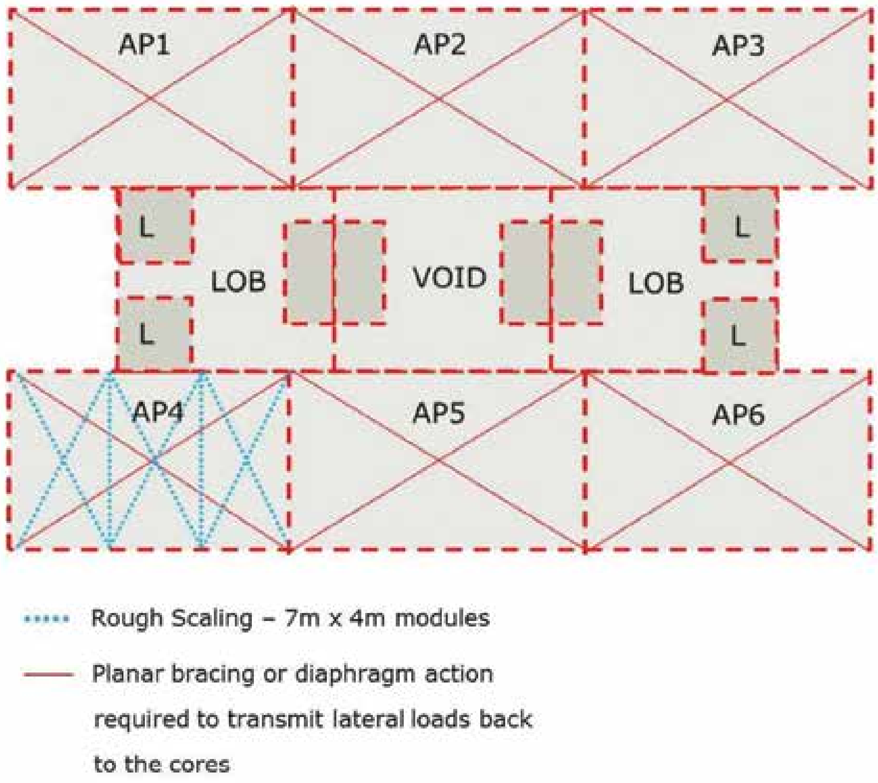


Figure 14. Prototype module (Source: Ramboll Group)

philosophy is also a hybrid where the upper stories are standard bolted end plate connections and the lower floors are joined with shear keys and the composite action. Figure 14 illustrates the prototype module.

This initial study shows that going tall and modular is technically feasible in one of the world's most active tall building markets.

The Future of Modular High Rise Buildings

Modular construction and PPVC have many advantages that are well suited for high rise construction. The modular approach has only been successfully implemented on a small handful of projects which break the 30 stories barrier. This barrier or modular ceiling is there for many reasons. Some of the reasons are technical which can all be resolved by implemented of well-tested approaches as outlined in this paper. Other reasons are pure market forces of supply and demand which limit the availability of tall building focused modular technologies and experienced contractors and manufactures. All of these challenges can be solved and will be solved in the next decade. In the future of tall buildings, modular design will have a big role to play.

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