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Applying Unit Modular In-Fill Construction Method for High-Rise Buildings

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***Abstract:** A modular construction method includes factory-prefabricated room-sized volumetric units. Although low-rise buildings have been constructed worldwide using this method for more than 30 years, it is a relatively new technology in high-rise construction. There are three basic methods of constructing high-rise buildings using modular construction: the core method, the core-and-podium combination method, and the modular in-fill method. While the first two have been used in the USA and in several European countries, the third method, introduced in 2011 by an international cruise ship development firm, is a rather new approach for which there are few case histories. Therefore, its applicability and construction feasibility should be verified. As a pilot study to test the applicability of the modular in-fill method, a 12-story residential building was built in Korea. This paper describes a case study of the pilot project. The advantages and disadvantages of the method and its applicability in terms of cost effectiveness and construction schedule management were evaluated.*

***Keywords:** Prefabricated Construction, Modular Technology, Modular In-Fill Method, Cost Effectiveness, Schedule Compression*

1. INTRODUCTION

Although modular technology has been used for over 30 years to construct low-rise buildings around the world, the technology is relatively new in high-rise construction, and there is increasing pressure to extend the technology to construction of buildings of 12 stories or more (Lawson and Richard, 2010). Three modular construction methods have been used to build high-rise buildings: the core method, the core-and-podium combination method, and the modular in-fill method. While the first two have been used in the USA and in several European countries since 2005, the third so-called cruise housing system (CHS), introduced in 2011 by a multi-national cruise ship development EPC (engineering, procurement, and construction) firm, is a relatively new approach (STACO, 2011).

The CHS approach has been used to design several high-rise student dormitories in Korea through a public–private partnership with the Korean government. However, because there is very little information available concerning the use of this method in high-rise building construction, its applicability needs to be verified, and the construction feasibility of the related techniques has to be evaluated to enhance the constructability of this method.

A 12-story student dormitory building has been recently constructed in Korea using CHS as part of a pilot project for a public–private partnership. This study was conducted to assess the applicability of CHS from the perspectives of construction cost and scheduling by performing a case study of the pilot project.

2. HIGH-RISE MODULAR CONSTRUCTION

There are three methods of constructing high-rise buildings using modular technology: the core method, the core-and-podium method, and the modular in-fill method. The first two methods utilize load-bearing modules, whereas the third method makes use of panel-based modules. Each method is described below.

Core Method

Load-bearing modules are typically used in modular construction for buildings up to eight stories high (Cartz

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and Crosby, 2007). The design of taller modular buildings requires additional considerations to ensure the overall structural stability of a building. One technique is to build a concrete core and stack modules around the core. The modules are directly connected to the core by attaching ties to cast-in-place plates in the core, so that compression is vertically transferred through the modules and the overall stability of the building depends on the core.

Core-and-podium Combination Method

Modules can be combined with steel or reinforced concrete frames and cores to enhance the flexibility of space arrangement by providing a podium structure. This approach allows successful construction in situations where the dimensional limits of the modules would otherwise be too constricting. The modules are placed on the podium, and the open spaces, along with the podium, can be used as commercial shops or parking areas.

Modular In-fill Method

This method adapts conventional construction techniques to building the frames of a facility. Figure 1 illustrates the construction procedures involved in the in-fill method. Reinforced concrete, steel, or precast concrete frames are constructed in the field in parallel with manufacturing of modules in a factory. The modules, designed to be independent, are then transported and in-filled into the frames on site.

This construction method offers the usual advantages of modular construction over conventional construction, such as a weatherproof construction environment, fewer on-site truck deliveries, less on-site equipment, fewer on-site construction activities, less construction waste, faster construction, and lower overall cost, while mitigating uncertainty concerning the overall structural stability of the high-rise modular building.

The structural behavior of high-rise modular assemblies is very complex because of the influences of eccentricities and tolerances in the module installation operation and the mechanism of horizontal force transfer to the core. By utilizing traditional construction methods to build the frames of a facility, the in-fill method enhances confidence in that the overall structural stability of a building is ensured.

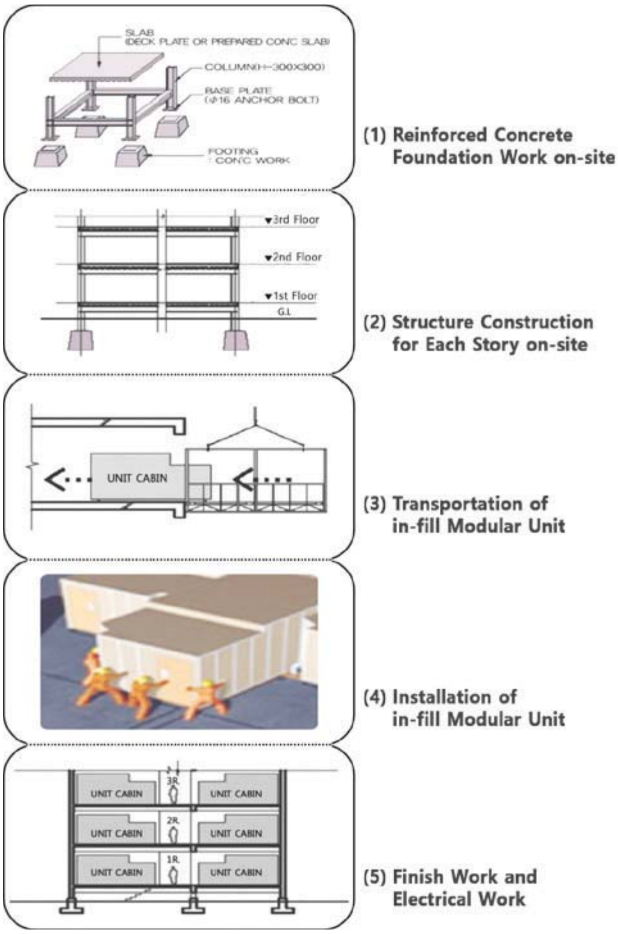


Figure 1. Procedures for Modular In-fill Construction Method

3. CASE STUDY OF THE IN-FILL METHOD

This study was conducted to assess the applicability of the in-filled method by performing a case study. The case study subject was a 12-story apartment building in Korea recently constructed using the CHS approach. The building has one basement floor and 12 superstructure floors, for a total of 3,700 m2 of floor area. The frames of the building are made of reinforced concrete structures. The first three floors are occupied by shops, and the fourth through twelfth floors are designed as apartments built along with in-filled unit-modules. Figure 2 shows a typical floor plan of the project.

Three types of unit modules were manufactured for the building, based on the CHS standard unit-module of width × length = 3,000 mm × 6,000 mm for a one-room apartment (A in Fig. 2), a two-room apartment (B in Fig. 2), and two bedrooms with a living room (C in Fig. 2). To satisfy the local building-coverage-ratio limit of 60%, the modules were manufactured in slightly larger sizes than the CHS standard, i.e., 3,250 mm × 6,200 mm, 3,050 × 6,150 mm, 3,100 mm × 6,150 mm, and 3,100 mm × 6,200 mm, for a building coverage ratio of 59.84%. The unit modules were uniformly 2,500 mm in height, and a total of 67 modules were in-filled.

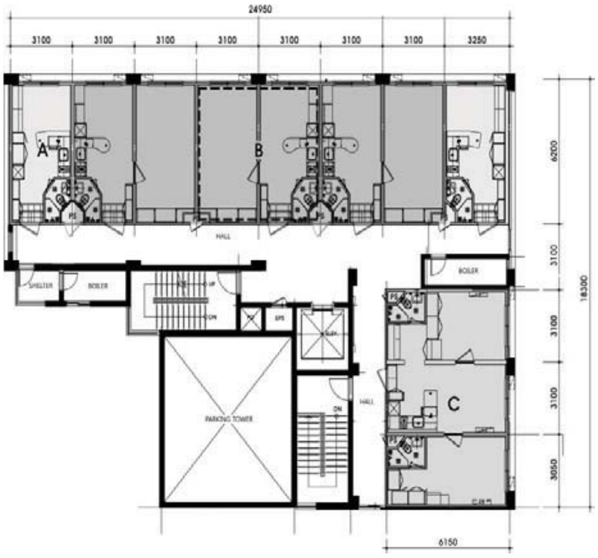
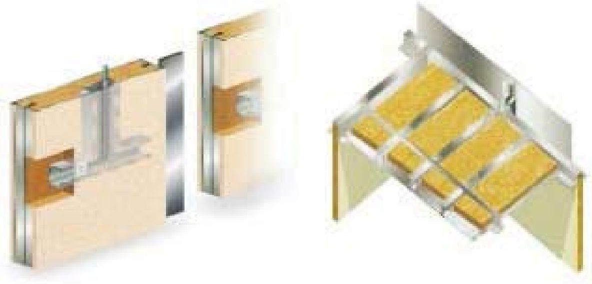


Figure 2. Floor plan of the Pilot Project

3.1. Prefabrication of Unit-Modules

Figure 3 illustrates the walls and ceiling panels used in the CHS construction. The wall panels were sized at length × width × thickness = 2,200 mm × 600 mm × 25 mm, 30 mm, 50 mm, or 75 mm (four thicknesses). The panels had a galvanized steel exterior sheet 0.6 mm thick with a polyvinyl chloride (PVC) film coating finish. The insides of the panels were filled with mineral wool, which provides excellent insulation and noise cancellation. The panel-to-panel joints were clip joints made of iron.



(a) Wall panels (b) Ceiling panels

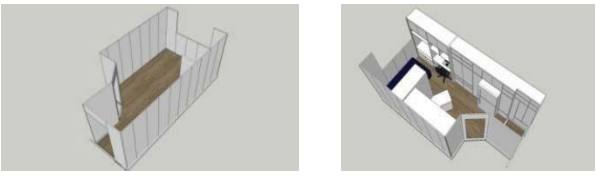
Figure 3 Wall and Ceiling Panels of the Modules (STACO, 2012)

The dimensions of the ceiling panels were length × width × thickness = 2,400 mm × 300 mm or 600 mm (two widths) × 25, 40, 50, 60, or 75 mm (five thicknesses). The ceiling panels were produced in various shapes and sizes for various purposes. Both the wall and ceiling panels had an error tolerance of 0.5 mm for the width and thickness and 3 mm for the length. Quality assurance was performed to ensure that each panel would be within the tolerance range.

The modules were manufactured according to the orders shown in Figure 4. Each module consisted of a living room unit and a toilet unit. The toilet unit was manufactured separately from the living room unit. The location of the bathroom unit is shown in A and B in Figure 2.

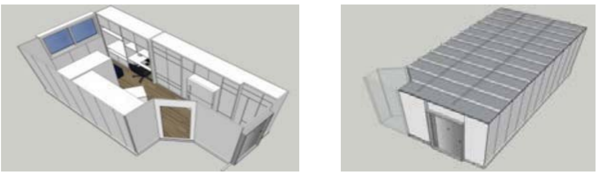
(a) Fabricating the bottom frame of a module with bolting and welding of C-channels

(b) Installing lower structural frame and bottom deck plate



(c) Standing up wall panels

(d) Setting interior facilities (piping, wiring, built-in furniture)



(e) Constructing exterior functional members (door, window, pipe duct)

(f) Installing a bathroom unit and finishing ceiling panels

Figure 4. Module Manufacturing Process

3.2. Transportation and Lifting

The prefabricated modules were transported from the factory by a 10-ton truck after installation of anti-swing devices to prevent any damage from occurring during transportation. During lifting of the modules, a balance bar was used to prevent twisting (Fig. 5 (a)). The modules to be in-filled first were the first priority for transportation and installed as soon as they arrived on-site to avoid problems such as moving line congestion and overstock of the modules on-site.

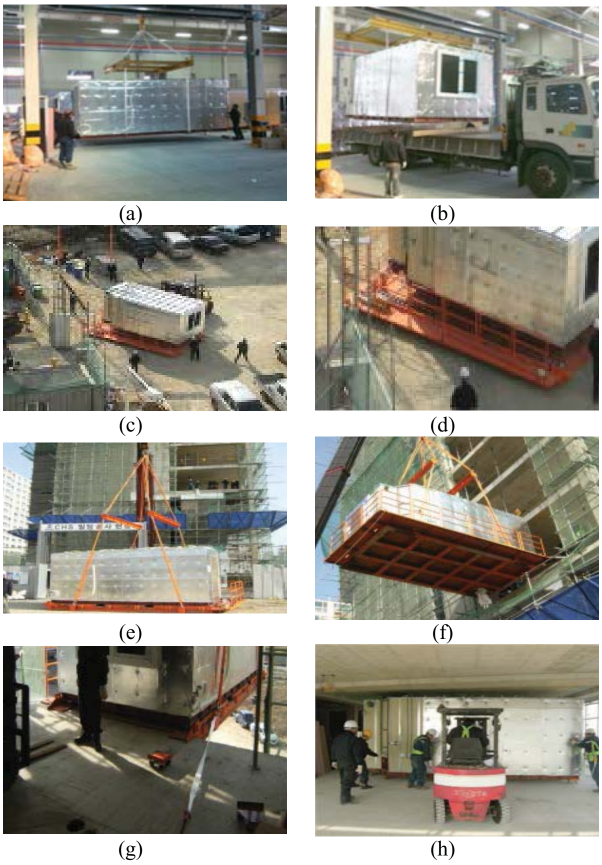

(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 5. Steps in Transporting and Installing Modules

Figure 5 illustrates the module installation process, from loading a module into a truck at the factory ((a) and (b)) to setting a module in a building frame at the jobsite ((g) and (h)). Figures 5 (c), (d), and (e) illustrate lifting a module to the building frame with a lifting device. Figures 5 (f) and (g) illustrate that the device was fixed to the edge of the installation target floor.

4. CONSTRUCTION DURATION ANALYSIS

The pilot building construction commenced in April of 2011 and was completed ten months later in January 2012. At the beginning of the project, a project management team was formed with engineers from the CHS design, production, and construction divisions. The project management team initially anticipated that a nine-month duration would be necessary for concurrent construction of the concrete frames and in-filling of the modules at the job site. However, the plan was changed to completing the overall frames on site first and then commencing the in-filling operation. This change was made to ensure a higher degree of safety, considering that the project was the first application of the in-fill method in Korea. In addition, the construction was halted from time to time because of delays in supplying the modules from the factory and coordinating the availability of a sufficient number of workers for construction of the reinforced concrete structures.

Based on the drawing shown in Fig. 4, the project management team planned that 11 modules would be installed on each floor. On the fourth floor, which is the first floor on which the modules were to be installed, four days were spent installing the 11 modules, at a rate of two to three modules per day. For the fifth through seventh floors, seven modules were lifted, and six were installed per day, resulting in a three-day duration. Two days were required to lift nine modules and install seven on the eighth and ninth floors. For the tenth floor, two days were required to lift 11 modules and install nine. As the number of installations increased, the skill of the workers in executing the lifting and installation processes advanced.

During the schedule planning stage, the project management team considered the distance from the factory to the job site. Because it took approximately 20 minutes to get to the job site from the factory and a 10-ton truck could transport one modular unit at a time, the ideal number of modules to be transported by one truck in a day was judged to be approximately six to seven, considering the loading and unloading times per module in the factory and at the job site. Given an average of 40 minutes required to lift one module at the job site, it was estimated that a maximum of 12 modules could be lifted in a day.

On-site building activities using modular techniques are expected to have shorter construction durations and require fewer daily on-site workers and truck trips than conventional construction techniques and therefore be less disruptive overall. To analyze the degree to which construction durations were reduced using the in-fill method, the three construction management professionals who participated in the workshop for the pilot project were asked to estimate the construction duration for a building of the same size as the pilot project using conventional construction techniques.

The responses varied depending on the experience of individuals but ranged from 12 to 13 months in the case of a reinforced concrete frame and from 10 to 11 months in the case of a steel frame. Comparing the numbers with the initial estimate of the pilot project duration, nine months, the in-fill method appears to provide a time-saving feature. However, given that the actual duration of the pilot project was 10 months, which included one month in addition to the initial estimate because of field safety concerns and module supply and worker procurement delays, the in-fill method was not judged to be superior to conventional construction in terms of minimizing the construction duration. Therefore, to achieve a time savings benefit with the in-fill method in comparison to conventional construction, it is necessary to conduct further research on interface management improvements.

5. Construction Cost Analysis

Table 1 summarizes the costs associated with the pilot project. Item (1) reflects the net construction cost of the reinforced concrete structures and mechanical, electrical, and plumbing (MEP) operations, excluding the module in-fill construction cost. The cost of manufacturing 67 modules and installing those on site totaled $1,617,700, which corresponds to a unit cost per module of $24,140 (or approximately $1,340 per square meter).

Categorizing the costs on the basis of the composition of a module, the highest costs were found to be associated with floor panel and bathroom unit manufacturing, which accounted for 27.3% of the unit cost of a module, followed by 21.4% for furniture production and installation, 12.1% for finishes and window installation, 10% for electricity, 8.8% for wall and ceiling panel installation, 8.6% for electrical appliances, 5% for transportation, and 3.8% for plumbing fixture installation.

Based on the total construction cost of the pilot project and the total area (3,700 m2), it is estimated that the net construction cost was $1,355 per square meter. However because this cost included furniture such as desks, dining tables, beds, and electrical appliances such as microwaves and refrigerators, if the costs of these items are deducted from the net construction cost, the total cost of the project was $4,608,500, or $1,245/ m2.

TABLE I. CONSTRUCTION COST ANALYSIS OF CASE PROJECT

Description		Net cost ($)
Reinforced Concrete Frame Work and Finish (excluding modules)	Construction	2,605,208
	Electricity	272,000
	Equipment	498,000
	Sub total	(1) 3,394,236
Modules	Manufacture	1,344,883
	On-site installation	272,892
	Sub total	(2) 1,617,775
Grand Total		(3) 5,012,010

The pilot project was compared with other building projects to assess the cost-saving features of the in-fill method. The comparison was conducted using 2012–2013 construction cost data for 186 public projects provided by the Korean Public Procurement Service (KPPS, 2014).

The use of public-sector cost data rather than private-sector data was expected to permit relatively consistent cost comparisons on the basis of government budget-based contract histories. Taking into consideration differences in the exterior and interior finish materials of public buildings, the construction cost distributions were in the ranges of $1,150/m2 to $1,350/m2 for reinforced concrete structures and $1,400/m2 to $1,600/m2 for steel structures. As mentioned earlier, the unit cost of the pilot project was $1,245/m.2

Although the in-fill method thus appears to achieve a slight cost savings, if the higher labor costs associated with conventional construction projects are considered, a greater benefit in cost savings is expected to be achievable. A recent study showed that the ratio between material costs and labor costs in conventional construction projects ranges from 50:50 to 37:63 and that labor costs are expected to increase further, accounting for up to 70% of total project costs, because of the shortage of experienced workers. (Korea Appraisal Board, 2013). The factory production environment of modular construction mitigates the labor-intensiveness of conventional construction.

One more prospective benefit of the in-fill method that needs to be further studied in examining its cost effectiveness is the economy of various aspects of the structural design. The average floor height of a reinforced concrete building in Korea is in the range of 3.6 to 4.5 m, depending on the complexity of the building. However, in a modular building, the floor height can be reduced by up to 3 m because a ceiling is not necessary and MEP pipes are not installed in the ceiling.

6. CONCLUSIONS

Three modular construction methods have been used to build high-rise buildings: the core method, the core-and-podium combination method, and the modular in-fill method. The first two have been used since 2005. The third, called the cruise housing system (CHS), was introduced in 2011 by a multi-national cruise ship development EPC firm.

Although CHS has recently been employed in the construction of several high-rise dormitories in Korea, there is very little information regarding its application to high-rise buildings. A 12-story residential building that was recently constructed with CHS was used as a pilot project. The main objective of this study was to assess the applicability of CHS from construction cost and scheduling points of view by performing a case study of the pilot project.

The pilot study building is a 12-story apartment building with one basement floor, 12 superstructure floors, and a total floor area of 3,700 m2. The frames of the building consisted of reinforced concrete structures. The main findings and results of the discussions in the workshops are summarized as follows.

From a construction duration perspective, for the in-fill method to be beneficial in comparison to conventional methods, it is necessary to conduct further research on interface management improvements. The construction of the pilot building required a total of 10 months. Estimates of 12–13 months and 10–11 months were obtained for reinforced concrete and steel frames, respectively. However, given that the actual duration of the pilot project was 10 months, the in-fill method was not clearly superior to conventional construction in minimizing the construction duration.

The pilot project was compared with other buildings to assess the cost-saving advantage of the in-fill method. Taking into consideration the differences in the exterior and interior finish materials of public buildings, the construction cost distributions were in the ranges of $1,150/m2 to $1,350/m2 for reinforced concrete structures and $1,400/m2 to $1,600/m2 for steel structures. The unit cost of the pilot project was $1,245/m2. Although the in-fill method was therefore slightly more cost effective, if increases in labor costs associated with conventional construction projects are considered, the in-fill method appears more economical.

REFERENCES

[1] Cartz, J. P. and Crosby, M., “Building high-rise modular homes.” *The structural Engineer*, Vol. 85, No. 19, pp.20-21, 2007

[2] Korea Appraisal Board, The Unit Construction Cost Data Book for the Evaluation of Property, 2013

[3] Korean Public Procurement Service, The 2012-2013 Construction Cost Data Book, 2014

[4] Lawson, R. M. and Richards, J., “Modular design for high-rise buildings.” Structures and Buildings 163 Issue SB3, *Proceedings of the Institute of Civil Engineers*, pp.151-164, June 2010

[5] Lee. D. H. and Ock, J. H., “A study on the application of the in-fill construction method to high-rise unit modular buildings.” *Journal of Architectural Institute of Korea*, Vol. 30, No. 3, pp. 105-114, March 2014

[6] STACO, Cruise Housing System with STACO Modular System, STACO Construction Inc., 2011