Title: **Estate Renewal Through Development of Prefabricated Super High-Rise Buildings**

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Subjects: Construction
Structural Engineering

Keyword: Construction

Publication Date: 2005

Original Publication: CTBUH 2005 7th World Congress, New York

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished

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## Estate Renewal Through Development of Prefabricated Super High-Rise Buildings

This presentation is based on a paper by Joo Ming Lau, Chee Hoong Shum, and Johnny Liang Heng Wong, all of the Housing and Development Board of Singapore (HDB).

HDB is the sole authority charged with the planning, development, design, and construction of affordable quality public housing for all Singaporeans. Since its inception in 1961, HDB has been credited with building more than 850,000 dwelling units that house about 86% of Singaporeans.

In the 1960s to ’70s, HDB successfully developed several medium-rise buildings, mostly 10 to 20 stories, to address housing needs. The Estate Renewal Scheme (ERS) was introduced in 1995 as part of the renewal plans for older HDB estates and towns where old residential buildings were redeveloped for more intensive use.

Innovation and challenge were the keywords used to describe the design and construction of HDB’s fully prefabricated 40-story tall buildings at Toa Payoh and Queenstown. These were the first two projects identified by HDB as part of the ERS to maximize land use in matured estates through the development of super high-rise buildings to replace existing low/medium-rise buildings. By building taller buildings, HDB delivers more homes in land-scarce Singapore, continually meeting the housing needs of the nation’s rising population.

This presentation will show HDB’s solution in the development of prefabricated super high-rise buildings to solve Singapore’s land scarce problem, incorporating full precast technology as an efficient and cost effective solution to renew its urban landscape.

# ESTATE RENEWAL SCHEME THROUGH THE DEVELOPMENT OF PREFABRICATED SUPER HIGH-RISE BUILDINGS


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## ABSTRACT


The Housing & Development Board (HDB) of Singapore is the sole authority charged with the planning and development of affordable quality public housing for Singaporeans. Since its inception in 1961, HDB has been credited with building more than 850,000 dwelling units that now houses about 86% of the population in Singapore.

Back in 1970s, HDB has successfully developed several medium-rise buildings, mostly about 10 to 20 storeys tall, to address the mass housing needs in Singapore. The Estate Renewal Scheme (ERS) was introduced in 1995 as part of the renewal plans for older estates and towns where old residential buildings are redeveloped for more intensive use.

Innovation and challenge were the keywords used to describe the efforts made in the design and construction of fully prefabricated 40-storey tall buildings at two of Singapore's town centres: Toa Payoh and Queenstown. These were the first two towns identified by HDB as part of the ERS to maximise land use through the development of super high-rise buildings to replace existing lower rise buildings. By building taller buildings, HDB hopes to deliver more homes in land scarce Singapore, continually meeting the housing needs of the nation's rising population.

This paper presents HDB's solution in the development of prefabricated super high-rise residential buildings to solve Singapore's land scarce problem, incorporating full precast technology as an efficient and cost effective solution to help renew its urban landscape.



**KEYWORDS**

Prefabrication, Estate Renewal, Public Housing

## INTRODUCTION

The Housing & Development Board (HDB) established in 1960 as a statutory board of the Ministry of National Development (MND) is the sole public housing authority of Singapore. HDB is responsible for the planning and development of affordable quality housing for Singaporeans. Since its inception, the HDB has built about 970,798 dwelling units, providing housing to about 86% of the nation's population. With only 650 $km^2$ of land competing for residential, industrial, commercial and other uses, HDB had the daunting task of not only providing affordable public housing, but also developing a total living environment to satisfy a growing affluent population.

Back in the 60's and 70's, the government was hard pressed to provide a roof over the heads of a rapidly expanding population. There was a serious shortage of housing for the people and due to the limited land space available, multi-storey housing was a choice solution. Back then, HDB leveraged on available engineering technologies to develop many medium-rise residential flats, ranging from 10 to 20 storeys tall, to address the housing needs.

In the 90's, HDB was faced with the challenge of maximising land use through the redevelopment of older residential estates. The buildings and facilities in older estates had gradually deteriorated over time. The ageing of these estates led to an outflow of younger and more mobile residents. If left unchecked, this will lead to a continuous decrease in the average disposable income of the residents of the estates. Hence the objective is not only to maximise land use but also to upgrade HDB residents' living in the older estates to newer and better flats. The **Estate Renewal Scheme** (ERS) was thus introduced to help redevelop and rejuvenate the older estates and towns. Selection criteria for precinct's redevelopment included high redevelopment potential and availability of vacant lands nearby for expansion.

To optimise land usage substantially HDB looked into the development of taller buildings to replace existing medium-rise flats. A survey conducted indicated that Singaporeans were receptive to the notion of high-rise living, primarily due to the weather conditions in the tropics as living higher is cooler and less affected by insect nuisance. After an extensive study, public housing undertaken by the HDB took on another challenge in the new millennium when it reached higher by introducing 40-storey residential buildings for two of its ERS projects:

a) **Toa Payoh RC30 (TP RC30)**: Development of four 40-storey residential blocks with a total of 927 dwelling units and a 5/4 storey carpark. Replacing four existing medium-rise residential blocks with only 400 dwelling units.

b) **Queenstown RC14 (QT RC14)**: Development of two 40 storey residential blocks, three 30-storey blocks and a multi-storey carpark. A total of 996 dwelling units were constructed to replace the existing 106 dwelling units.

These two projects challenged HDB engineers to come out with suitable structural systems that would be efficient, cost effective and resilient against lateral effects from strong winds at high attitude and far field tremors from the Sumatra Trench. It also challenged the design team to take into consideration the buildability of these tall structures using precast technology to achieve higher quality and construction productivity.

## CHALLENGES

From the start, the design team knew that many factors needed to be considered and planned for early to ensure the success of the projects. Some of the challenges identified during planning stage included:

a) Wind and tremor designs
The design of the tall residential flats required engineers not only to consider the stability of structures under lateral effects such as strong winds and far field tremors from the Sumatra Trench, but also the comfort level of the residents residing at the topmost storey with regards to sway. Suitable structural frames were thus introduced for these buildings based on relevant codes and building guidelines. In fact

HDB also collaborated with a local university, the National University of Singapore (NUS), to conduct wind-tunnel tests on the proposed tall buildings.

b) Redevelopment over existing buildings
As both projects were redevelopment projects, the proposed tall structures had to be constructed over demolished sites. One of the many challenges presented was the presence of existing piles. As there were no proper records of the pile layout for the existing buildings, extracting all the piles would be a too expensive option. HDB instead opted on the use of a large pilecap foundation supported by large diameter bored piles, which allowed engineers the flexibility of moving the positions of the proposed piles should existing piles be encountered.

c) Nuisance caused by construction activities
As the proposed buildings were constructed in developed housing estates, there were concerns that the intense construction activities may result in untidiness, dust, noise, air pollution, traffic congestion, etc.; all of which presented constant nuisance to the residents of nearby buildings. There was therefore a need to look into the reduction (or elimination) of inconveniences and disturbance generated from the proposed construction. After considering all available alternatives, HDB opted for a fully precast solution, which not only allowed faster construction turnaround time but also reduced nuisances generated, as most of the construction activities were moved to precast yards located away from the city.

d) Limited construction space
The construction sites for both projects were also relatively small, resulting in intensive development of land areas. Hence, there was a need to consider the restricted space available for material and equipment storage. HDB worked with the contractors and precasters on a just-in-time precast delivery system and also made special provisions in the designs to allow precast components to be stored temporary at the proposed multi-storey carpark area. The just-in-time delivery system was successfully implemented through proper project management planning and exploitation of information technology, like web-cam monitoring system and material management system.

e) Construction Safety
For the construction of such tall structures, safety of the workers working at great heights was a major concern. The design approach taken was to produce designs that required very minimum in-situ and external works to be carried out. Most of these external works and architectural features and finishes were in fact done at the precast yards. As for construction planning, besides introducing the Automated Building Construction System (ABCS) for one of TP RC30's blocks, HDB also introduced the Climbing Safety Working Platform to enhance overall productivity and safety on sites.

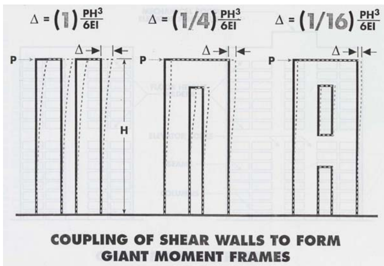
f) Cost
Cost was also a major concern for the two projects and every effort was made to come out with a cost-effective design without compromising structural safety.

## DESIGN INITIATIVES

Having identified the key challenges, the architects, engineers and project managers involved in the projects worked very closely to come out with several suitable building layouts and configurations. All alternatives were reviewed for constructibility, economics, aesthetics, functionality, structural stability and safety.

### Adopted Structural System
In essence, a compact and relatively symmetrical layout was preferred as it produced ideal response against lateral forces and construction efficiency. Besides adopting the rigid framing system and strategically placing the lift and household shelter shear cores in the building layout to help stiffen the tall structures, the design team also used the 'Giant Moment Frame system' (Alfred Yee, 1991) to provide additional lateral stiffness for the buildings.

Tall buildings being less stiff are susceptible to sway and twist in both longitudinal and lateral directions due to lateral loads caused by wind and notional effects. The Giant Moment Frame system (Figure 1) was thus integrated into the structural system of the buildings to help improve the human living comfort, especially at the topmost few storeys. This was done without compromising on the units' layout at each storey. The giant frame was integrated into the structural system by introducing deep wall girders at roof level to help tie the critical shear and/or core walls together in both orthogonal directions to enhance the overall stiffness of the structure. By tying the key shear walls at roof level, analyses conducted indicated that lateral deflections of the buildings could be reduced by as much as 20%.



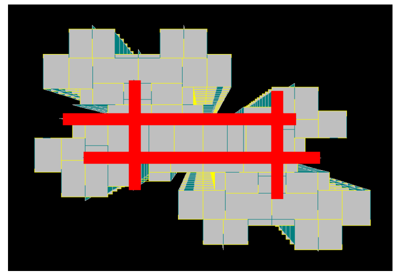



Figure 1: Giant Moment Frame used increase building's stiffness

**Integrated Analysis, Design and Detailing**
Once the shape and layout for the buildings were established, 3–D computer models using the software SE CAD were generated to perform analytical simulations on the buildings.

In an effort to strive for higher quality and productivity in structural engineering design and drafting, HDB had developed an integrated computer-aided analysis, design and detailing software known as SE CAD. One of the unique value-added feature of SE CAD lies in its extensive databases which captured HDB's accrued technical design, detailing and systems, field tested over two decades of refinement and focused on enhancing the buildability of structural system. Once the shape and layout for the tall buildings were established, their structural behaviors were simulated using SE CAD. By integrating the analysis, design and detailing works, SE CAD not only helped to speed up the design process and increase productivity in the design office, but also allowed the team to exploit HDB's experience in prefabrication and design through the use of the incorporated databases.

**Foundation Design**
Due to the high column loads within the limited footprint and very dense soils encountered at shallow depths, higher capacity bored piles were used instead of steel piles. Besides being an economical choice, it helped to reduce the number of piles installed and thus avoided overlapping of soil stress envelopes, thereby reducing the soil stress between piles. In addition, as structural columns were also closely spaced, large pilecaps supported by large diameter RC bored piles were used. Such large pilecaps helped to tie up the bored piles – producing better resistance against shear failure from earthquake forces. As mentioned earlier, the contracts were all redevelopment projects and the proposed buildings were constructed over demolished sites. The presence of the existing piles presented a challenge, as there is a need to avoid the old piles when planning the new pile layout for the building. Hence, the choice of using large pilecap foundation provided the advantage of allowing the positions of piles to be moved when existing piles are encountered.

**PREFABRICATION STRATEGY**

The buildings for the two mentioned ERS projects were specially designed almost fully precast (more than 90%) to enhance buildability and constructibilty on site (see Figure 2). Besides using the conventional precast components for these buildings, new innovative precast components like the precast hollow-core walls, large precast wall panels, integrated precast components and prefabricated toilets were introduced. Prefabrication was necessary for the projects to speed up construction processes and reduce noise generation. Right from the start, an integrated design approach was adopted for these projects. Regular meetings were held with contractors and precasters to go through the precast strategy. The purpose was to obtain feedback from all parties for an economical and buildable solution.

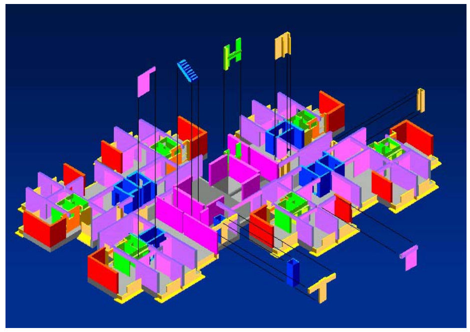



Figure 2: Fully Precast System used for super high-rise construction

**Modulation and Standardization**

HDB adopted a modulated grid layout concept as the basic building block for the design of its super high-rise buildings. At macro level, it maximized repetition of specific block types clustered around a network of social amenities to form the precincts. At block level, standard unit types were ingeniously arranged to yield several ranges of block layouts. Arranging the same unit types to run on repeated grids helped achieve optimum number of precast component repeats which in turn led to reduction in production cost as there were less variations in precast moulds and workers were more familiar with the works. For these projects, the design team had managed to achieve as much as 400 – 500 repeats for some of the precast façade components.

**Size and weight of precast components**

As it was important to consider the constructibility of the buildings during design stage, all precast components were carefully planned, designed and detailed. One major consideration was to consider the feasible weight and size of all components to ensure ease of transportation, erection and installation. After studying all factors including the economical lifting capacity for the cranes and the Automated Building Construction System (ABCS), used for one of the blocks at TP RC 30, a weight limitation of 8 tons was set for all components. Looking through the list of precast components used, three component types exceeded this weight limitation: precast walls, precast household shelters and precast water tanks. Innovative solutions were thus developed to counter these weight problems for these components:

a) Precast walls

One notable innovation that sprung out from these projects was the introduction of the **precast hollow-core walls** (see Figure 3(a)). Conventional precast columns and walls were usually cast as a single unit and connected to the buildings through the use of proprietary connectors. These presented problems as the 8 tons weight limitation would limit the maximum length for solid precast walls to only 4 m long. For these projects, the lengths of the walls ranged from 2 m to 9.8 m. Further, due to the high column forces and moments involved, the number of connectors used would be relatively high. This presented concerns over possible erection and installation problems. To counter the above, HDB developed its own precast hollow-core walls. The introduction of cores not only made the walls lighter but also easily allowed connectivity to be achieved by pulling the reinforcements through the cores, therby reducing the number of connectors used.

b) Precast Household Shelters

To ensure all Singaporeans are better protected in the event of armed hostility the design and construction of a civil defence shelter in all residential homes in Singapore became mandatory in 1998. In peacetime, these shelters (3 $m^2$ to 4 $m^2$) doubled up as convenient storerooms. These shelters were also introduced in TP RC30 and QT RC14. As the walls were heavily reinforced, the components were prefabricated as a single 3-D element at precast yards before being transported and installed on site. To reduce the weight of these components to a manageable 8 tons, the **precast 3-D hollow core household shelters** (see Figure 3(b)) were introduced. The household shelters could also be broken into 2 – 3 components which were joined together on site using specially designed loop joints.

c) Precast Water tanks
Since 1987, HDB had started using durable precast concrete water tanks for its buildings. However, due to the weight of these tanks (i.e. 13 tons without its cover), they could only be economically installed in buildings up to 55 m in height (about 16 storeys). For the 40 storey tall buildings, HDB creatively used its own in-house developed **segmental circular ring water tank system** (see Figure 3(c)). Each tank module consisted of a base ring standardized at 1.1m height and diameter 3.52m. To meet the desired storage capacity, the tank was extended upwards by snapping on a series of standard 1.3m high concrete rings weighing 2 tons.

(a) Hollow-Core walls (b) 3-D Hollow Core Houshold shelters (c) Segmental ring water tanks

Figure 3: Innovative precast components introduced to limit the size and weight of components used for the project

**Integration of Components**
Wherever possible, components were integrated to form a single element without exceeding the weight limitation of 8 tons, e.g. the precast beams and facades were designed as a single component. Such integration led to faster construction as it reduced the number of lifting operations required on site, consequently reducing the workloads on the cranes. All architectural features were also integrated to the precast components, reducing external works on site. This greatly enhanced safety on site.

Besides integrating the components, integration of the sanitary and electrical services with precast components were also performed. The electrical conduits were in fact cast into the precast wall panels/partitions, and the integrated panels transported and erected on site with the electrical services.
Although the areas occupied by toilets were small, the construction cost for the toilets could reach 15% – 20 % of the unit's cost. This was because of the quality wares provided, as well as the dependency on skilled labor. Construction of toilets had conventionally been highly labour intensive and unproductive, due to the various components involved and many different trades required for the job (about 11 trades with a total of approximately 57 visits). To enhance productivity on site, HDB opted for the use of its in-house developed prefabricated boxed-toilets (Figure 4). The toilet system essentially consisted of a precast reinforced concrete floor, tiled in the factory with necessary floor traps and pipes buried in the slab. The walls were made of galvanized steel sheets bent into c-shaped panels and clipped together for strength. Tiles were attached to the steel panels by tile adhesive. The completed boxed-up toilet was then transported to site and erected to its final position in just one operation. The weights of these boxed toilets were well below 8 tons.

Figure 4: HDB’s Prefabricated Boxed-Toilet

## CONSTRUCTION AND SAFETY INITIATIVES

### Foundation Construction

The large pilecaps used for the foundations were about 2.1 m thick (grade 50 concrete) and due to the large pours involved, special provisions needed to be taken on sites during construction phase. First, considerations need to be made for the heat and noise generated. In order to reduce the nuisances caused, pouring of concrete was restricted to 7am – 7pm. The casting of the whole foundation was also divided into approximately four stages to allow the pouring of concrete to be completed in a single day for each stage. For temperature control measures, besides high-slag blast furnance cement to SS 476 with 73% slag being used, chilled water was used on the initial mix. Controlling the temperature gradient between the core and the surfaces was also done by placing 50 mm polyform on the vertical faces of the raft and covering the top surface with 50 mm polyform boards followed by polythene sheets. Instrumentation was set up to verify the effectiveness of the temperature controlling measures.

### Precast Erection and Installation

With over 30 different types of precast components used, besides design considerations, careful precast erection and installation planning was also critical for these contracts. HDB worked very closely with the various parties involved and came out with an installation strategy to ensure minimum delays on site. Positions of cranes were mapped out on site in consultation with the safety officers and anti-collision systems were installed to enhance overall site safety. HDB also implemented **the Climbing Safety Working Platform** for the very first time in these projects as an alternative access platform to facilitate precast erection and construction activities. These working platforms followed the floor under construction as shown in Figure 5. The use of these platforms helped increase productivity on site as there was no need to assemble and dismantle scaffolds with safety netting from ground floor to roof. It also provided a neater work area and helped free up the storage space for scaffolds for other use.

Figure 5: Climbing Safety Working Platform used to enhance safety on site.

As part of the installation strategy, the precast façades / external peripheral walls were also used as temporary safety barricades for construction. As such, they were installed first followed by the installation of the precast planks. The composite slab system was used for both projects, where a structural concrete topping was cast over precast planks to form the RC slab. These precast planks served both as working platform and formwork, thereby reducing the need for erecting and dismantling formwork. To further enhance site productivity, 'unpropped' planks were also implemented for these contracts. These planks were designed to take both the construction load and weight of the wet concrete without the need to erect temporary props for support. Internal components such as precast hollow-core walls, integrated large panel partition walls, precast hollow-core household shelters and prefabricated toilets were then placed in position.

**Exploitation of Information Technology**

HDB introduced the **Precast Inventory Tracking System** to help manage the large number of precast components implemented in the two ERS projects. The system essentially enhanced the monitoring and tracking of precast components used on site. Basically, all precast components produced at the prefab yards were tagged with electronic bar codes. The electronic tags contained useful information such as component ID, weight and location for erection. These tags were all computerized in a central database and tracked from delivery up to erection stage. The system also allowed engineers, precasters and contractors to receive up-to-date inventory status of the precast components on site. Webcams were also installed on both sites to allow on-line monitoring of the projects' progress through the internet. Such facility allowed precasters to use the information to help plan production schedules and retrieval of trailers from sites.

**Automated Buildings Construction System (ABCS)**

To further speed up the construction process and to increase productivity on site, HDB invested on the use of the **Automated Buildings Construction System (ABCS)** for the construction of one of the residential blocks at TP RC30 (see Figure 6). It was the very first time such a system was used for the construction of HDB buildings, and it allowed HDB to study the effectiveness of using such a building system for the construction of tall buildings. The ABCS essentially consisted of a self-climbing temporary roof supported by four tower masts. The roof shelter provided an all weather shelter for construction activities to take place without disruption caused by adverse weather conditions.

The ABCS also came with an advanced mechanized and computerized material management/transportation system to help expedite the erection and installation of precast components. Basically when a precast component needs to be hoisted to the working level, a signal will be sent to the crane operator. The ID of the component will appear on the touch screen monitor in front of the crane operator. The crane operator proceeded to activate the auto transport system, which would automatically transport the component to 1m above the installation position. The installation process will then change to manual mode for workers to take over. Such a system helped increase productivity by as much as 30%.

Figure 6: Automatic Building Construction System (ABCS)

## CONCLUSION

As part of its estate renewal planning and maximisation of land usage in its older housing estates, HDB had introduced the replacement of its medium-rise buildings with 40-storey tall residential buildings for two of its ERS projects: TP RC30 and QT RC30 (see Figure 7). Such redevelopment programmes had successfully increased the number of dwelling units from 400 to 927 for TP RC30 and 106 to 996 for QT RC14. Several challenges were encountered during the design and construction of these super high-rise buildings. However, HDB had successfully exploited its vast experience in design, prefabrication, precast and construction technologies to meet these challenges and produced an efficient, high quality and cost effective building solution. HDB had also successfully exploited advanced building and material technologies to enhance both site productivity and safety for these projects. Finally, several engineering innovations and achievements were derived which will better prepare HDB to meet greater challenges in the near future as it looked to the development of taller buildings to solve Singapore's land scarce problem for mass public housing.

(a) TP RC30 (a) QT RC14

Figure 7: Completed blocks at TP RC30 and QI RC14

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