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In inner cities worldwide, there is limited availability of large land parcels apt for high-rise development. Yet, given the seemingly global trend of "superslim" architecture, this limitation does not preclude building skyscrapers on smaller sites in city centers. Considering the Phoenix Apartments, a superslender tall building completed in Melbourne in 2013, this paper reviews how slenderness can impact technological innovation from a perspective of construction management.

Introduction

Built on a block of land with the dimensions of 6.7 by 24.5 meters, the Phoenix required an integrated approach to resolve site access, structural engineering, cost control, labor productivity and risk management. At the end of the construction process, an innovative methodology of vertical construction emerged; the result was an unconventional development driven by technological result, rather than by economic return. In the context of the Australian building industry, the Phoenix was a prototypical exercise of superslender tall building technology. The experience of this single project defined a model of construction management that fed into other local developments with an innovative approach that pursues rapidity in construction. A qualitative review of technologies, means and methods of construction of this project calls for an integrated approach of slim vertical construction, which, in the future, could be characterized by an almost simultaneous extrusion of structure and building enclosure.

A Construction Standpoint on Slenderness

There is considerable interest in superslim residential towers. This building type can be defined, summarily, as towers of unusual slenderness ratio, in excess of 1 to 10. Often they exceed 1 to 15, which is considered suitable in extremis for a service core (Sarkisian 2012). These buildings attract interest for their architecture, and the socioaesthetic aspects of the phenomenon have been debated widely in the media,

Figure 1. Phoenix Apartments, Melbourne.

particularly in connection with the production of niche upmarket apartment buildings (Goldberger 2014; Hansen 2016). This typology has been analyzed by the CTBUH, where research and industry contributions came from two prevalent standpoints: structural engineering and socioeconomics of development, with the latter focusing particularly on New York City (Barr 2015; Willis 2015). Reports on slender towers by Australian newspapers suggest that the phenomenon may be diffused globally. There are signs that similar patterns of development – at lower heights than New York – are emerging in Melbourne particularly, as indicated by the frequency, location and type of recent residential projects in the inner city (Rollo 2013; Pallisco 2013; Green 2014; Lucas & Dow 2014; Marfella 2014).

This article considers factors of technological innovation in the process of superslim construction. Qualitative building case-study research – in this case focused on the construction of the Phoenix Apartments, a small superslim residential tower in Melbourne – was used as a methodology of investigation. Using a range of sources, which included project documents, site-based observations of the construction process, and access to project records, the building was analyzed, considering the technological decision-making of the head contractor. In synthesis: what was the effect of slenderness on the management of the construction process?

Notwithstanding the limitations of a single case study, this project signals a path of relevance for further research – at least at the level of regional significance. The project was built – and its results used by the head contractor – as part of a deliberate business plan to establish a methodology of development and construction management suitable for other projects of similar use, scale and site conditions. In 2010, Equiset, a development and construction firm, commissioned a study to seek a business strategy for the implementation of "rapid vertical construction" in Australian high-rises. The strategy was designed to unfold in three steps with three superslim projects, and started in Melbourne with the Phoenix Apartments.

The Skinny Challenge

The Phoenix Apartments is a 29-story tower built on a small parcel of land at 82 Flinders Street, in the inner city grid of Melbourne (see Figure 1). The tower sits on a narrow rectangular site of 6.9 by 24.5 meters, which is comparable in size to that of a Victorian terrace house. The first concept of the building, as submitted for town planning approval in 2010, envisaged a 143-meter-high tower with slenderness ratio of 1 to 22. Following mediation with the City of Melbourne, the initial scheme was shortened to 102.5 meters, and the slenderness ratio to 1 to 16 (see Figures 2 and 3).

The challenge to transform such a small footprint into a feasible tall building concept, both at an economic and technical level, was unprecedented – at least in Australia. Evidence of previous projects that could demonstrate technology and profitability of a tower of such "skinny" proportions was not easily obtainable. The initial superslim scheme posed challenges of structural engineering to control rotational sway. The shortened scheme simplified the task of controlling wind-induced accelerations, for example, by avoiding the need for a tuned liquid damper, and reducing the entity of side-sway, which could have caused encroachment on adjoining properties (see Figure 2). A shorter building, however, exacerbated economic challenges, as the loss of revenue from cutting the top floors was such that profit outcomes became more uncertain.

The reduction in height impacted the construction budget, which had to be reduced to the point that standard labor and equipment-hire rates would not suffice. Due to the entrepreneurial determination of the property owner, who was eager to own and occupy the penthouse of the building, the project proceeded with less-than-ideal fundamentals of development. It was equally vital that the head contractor took interest in the project by foreseeing an opportunity to test a new typology of residential development.

Figure 2. Early scheme showing slenderness ratio of 1 to 22. © Fender Katsalidis Architects

Figure 3. Phoenix Apartments final scheme showing slenderness ratio of 1 to 16. © Fender Katsalidis Architects

Figure 4. Early construction works on the site. © Fender Katsalidis Architects

Being located in proximity of a major intersection of the Central Business District (CBD), the project presented unique challenges of access, both for construction and occupation (see Figure 4). The impracticality of excavating an infill site of very narrow dimensions excluded the possibility of an ordinary basement with ramps; even a podium car park was not possible. Vehicular access for the residents was therefore resolved with an above ground automatic car stacking system, which occupies 10 floors at the rear of the plan (see Figure 5, left).

The challenges of access during the construction stage were of equal concern. The main frontage of the site is opposite a busy tram junction that prevented regular access for large construction vehicles. The rear of the site, facing the narrow Malthouse Lane, required 24/7 access for the public and adjoining owners. The head contractor was involved in the design review process and gave direct input, through a series of workshops on preferred technologies, until an approach that met unit cost, architectural outcome, engineering, and client requirements was found. The initial engineering scheme, developed at the town planning stage, was altered in conceptual terms. The first take on the structure was based on a sitewide central concrete core, complemented by two steel skeleton sections at the front and rear. Although orthodox in engineering principles, the initial concept seemed to bear too much risk against tight cost and construction time requirements. Once the material handling limitations of the site became clear, a radical reformulation of the engineering approach became necessary.

The ensuing collaboration between client, architect (Fender Katsalidis Architects), structural engineer (Robert Bird Group) and the head contractor generated an alternative where the solid component of the core was expanded with two prolonged fins running along the boundaries of the site (see Figure 5, right). The new engineering concept transformed the Phoenix from a

Figure 5. Typical plans showing the the automated car stacking at the rear of the building and the double-H structural configuration. © Fender Katsalidis Architects

"Despite simplicity of conception and operation, jump-forms require onerous cost and time allowances to be made at the start of the project; these costs, generally, can be recovered only if the project is above 15 stories high."

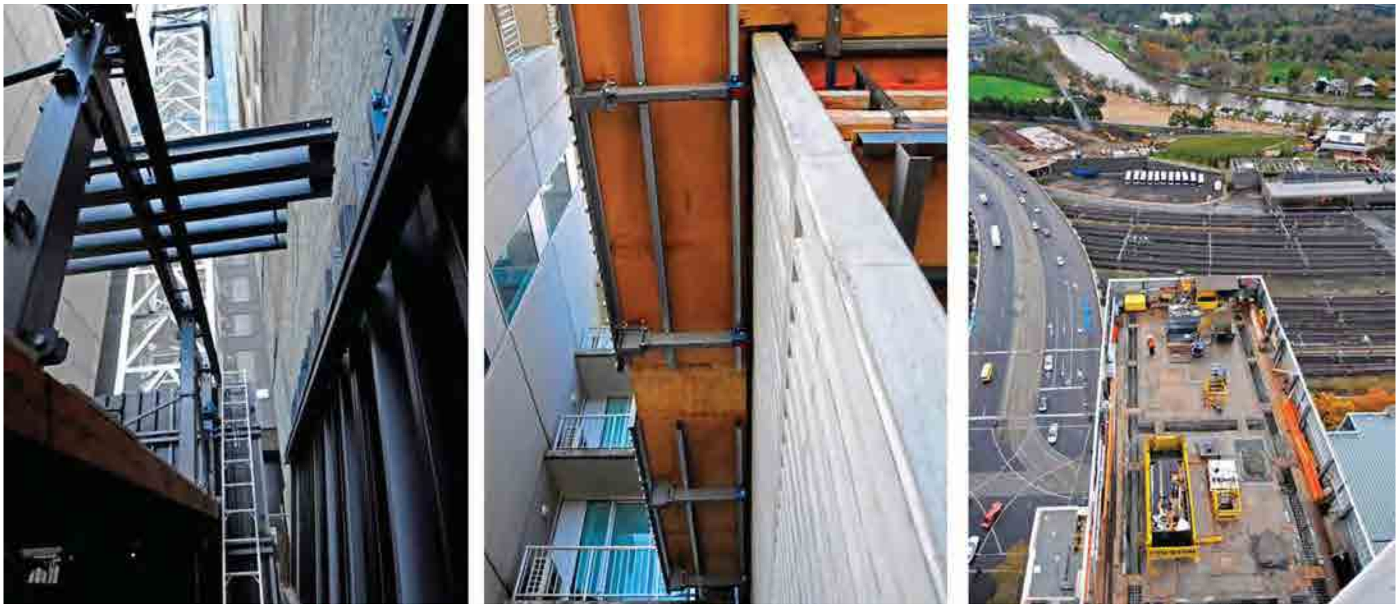

Figure 6. The structure and part of the envelope were rapidly built using a self-climbing jump-form system.

conventional composite steel-concrete tower to an all-concrete structure with a robust double-H beam configuration in plan. More significantly, the benefits went beyond structural engineering; the new structural concept allowed meeting the tight budget by way of minimizing the trades and building technologies required.

The "Jumping" Phoenix

Having considered the contextual conditions of an expensive labor market, the technological choice for the construction of the primary structure of the Phoenix fell on the development of a customized concrete "jump-form" system that could holistically accommodate vertical elements and eliminate the need for primary structural steelwork (see Figure 6).

Concrete jump-forming is a construction method that minimizes material handling by lifting formwork automatically on a floor-by-floor basis. The technology is a type of self-climbing formwork, which is alternative to the older – but still practiced – method of "slip-forming," which consists of the continuous sliding of formwork. Jump-forming is activated by hydraulic rams, which typically sit on lifting beams engaged with concrete walls under construction. Once concrete sets with sufficient strength, the rams push formwork to "jump" from the most recently poured wall to the next level. In essence, this method of construction is independent from primary cranes and relies solely on hydraulic action to lift formwork components.

Historically, in Australia, jump-forms have been productive for vertical concrete construction by progressing rapidly ahead of program. Assembling materials and forms for each "jump" pour does not require highly skilled or time consuming labor on site, which traditionally – at least for the Australian industry – are considered more difficult to handle with slip-forming (Egan 1984). The roots of this automated in situ construction are deeply set in the local industry, particularly in Melbourne, where this technology was invented, patented and has been developed since the mid-1970s (Schmidt 1976). Despite simplicity of conception and operation, jump-forms require onerous cost and time allowances to be made at the start of the project; these costs, generally, can be recovered only if the project is above 15 stories high (Shaw 2014).

As a 29-level building, comparable in size to a service core, the Phoenix was a suitable project to adopt jump-forming. The construction of this project, however, required fine-tuning this technology beyond the common practice to erect a core. The idea of "jump-forming" an entire building structure – including parts of the envelope – required off-form quality to be acceptable as architectural finish. To prevent shabbiness and unsightly cold-joints, the external facing of the structure was ribbed. Involvement of the concrete manufacturer Boral, which developed a mix specifically for the project, was equally important in order to reach an

Figure 7. Close-up view of jump-form ribbed, in situ concrete façade.

acceptable quality of finish (see Figure 7). Other challenges were posed by the open double-H plan configuration, which was dissimilar to the typically closed, stiff box of a concrete core. The open elongated ends of the structure needed to be tied at the wall extremities.

Jump-forms, generally, can adapt to different projects with small adjustments to fit different core layouts. The level of modular adaptation of existing systems was not sufficient for the Phoenix, and a new, patented version of the system was developed by Sureform Systems (Shaw and Stella, 2013). Innovation in the new system consisted of different positioning of hydraulic rams, and configuration of overhead grillage and lifting beams, which, given the tight footprints on the site, had to be located closer to external walls than with other systems already available on the market (see Figure 8).

This monotechnology, all-concrete approach, and the level of project-tailoring of the jump-form, resulted in a construction site where vertical handling of materials was reduced to the bare minimum. Capital-intensive automated formwork was complemented by low-tech solutions. Crane time availability allowed pouring by kibble – a seemingly old-fashioned method for a contemporary high-rise – in place of the common, but more site intrusive, vertical concrete pump lines.

Construction efficiency allowed crane time to be used for lifting large preassembled reinforcement cages directly inside the jump-forms, cutting labor costs.

Means, Methods, and Knowledge Transfer

The site conditions of the Phoenix had repercussions on supply chain, workforce organization and project planning. In order to gain maximum control of time, cost, and quality, and given the difficulty of hiring subtrades competitively, due to the unusual "quantities" for a high-rise tower, the contractor managed the project in a radically different way. The contractor took a direct

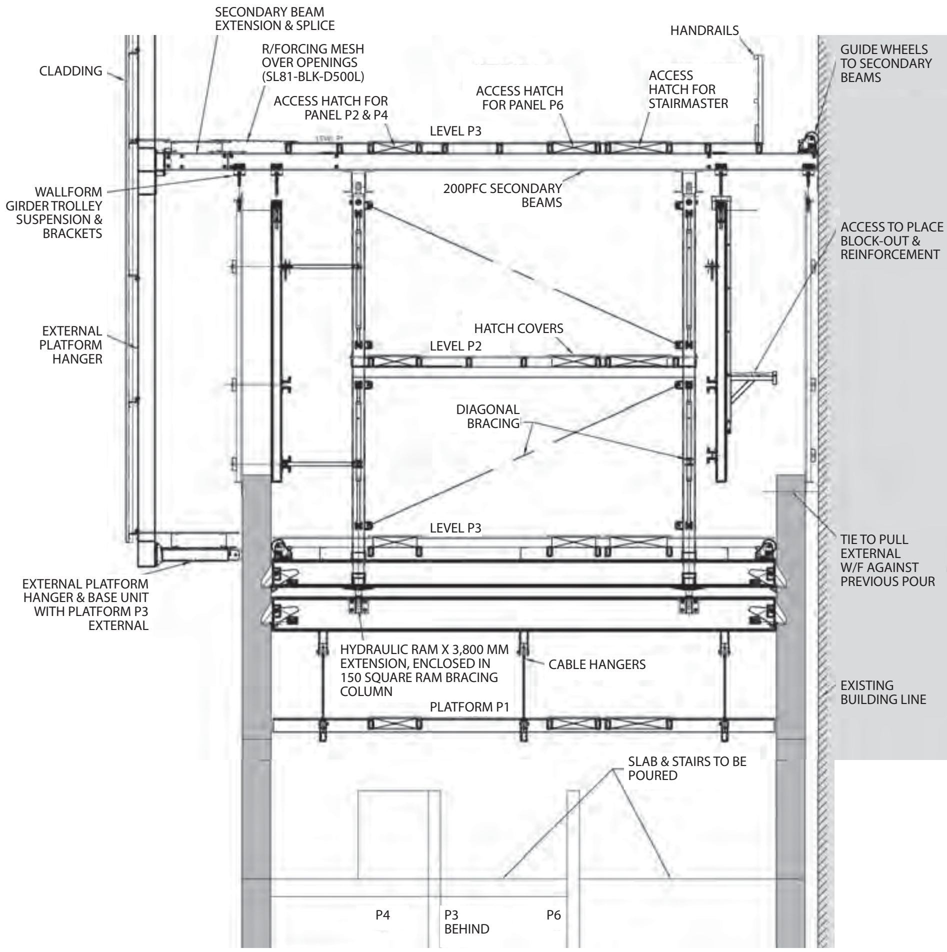

Figure 8. The jump-form system configuration for the "Jumping" Phoenix.

stake, supervising actively a number of site activities related to the installation and operation of the jump-form. While automated formwork traveled reliably, the most labor-intensive parts of the structure were handled as half-assembled off-site components (e.g., reinforcement cages). This occurred, however, by avoiding full off-site prefabrication. In essence, the scale of the project, and the need to control the rapid, simultaneous and integrated construction of structure and building envelope, triggered a partial "in-house" approach to lead contracting.

The workforce was organized on site according to flexible skills, and by compressing within a handful of floors the front face of construction. Typically, in a high-rise tower, construction proceeds vertically in distinct sections, which spread across a large number of floors. The sequence starts with the construction of the core over several floors (from 5 to 10), and it is followed by a handful of floor structures and perimeter frames. This second section of activity is generally a high-risk zone bounded by safety screens. Depending on the technologies used, it is not uncommon that this part occupies more than five floors, including provision of back propping. The trades associated with the building enclosure follow – below and after – under the safety screens; these may occupy another handful of floors protected by edge railing. Then, finally, finishing trades, completion of services and fit-out follow, staggered and spiraling from the bottom up. This vertical layering of trades generally moves following an ideal "corkscrew" trajectory, where a single trade is organized to follow work in subsections of the floor plan (in two to four zones, depending on the size of the floor plate). Each trade proceeds by first shifting or rotating on the floor, and then moving vertically to the next level, using vertical circulation and services (stairs, electricity and temporary "builder" lifts), which were built and installed earlier in the core. In this method of construction, 10 to 20 floors of construction activity, from the front-face of the tip of the core to the lowest floors of the façade installation zone, can be underway simultaneously.

This conventional process could not be adopted in full at the Phoenix. The impossibility of working at ordinary market rates of construction imposed a rigorous schedule, which subsequently had to be handled by "compressing" the construction activity of the shell (core/structure, envelope, and primary services) in a vertical zone that was between one-half and one-third the height of a conventional commercial high-rise building. The construction of the jump-formed core was completed generally in a zone of three floors. Typically, only another three floors below were required to complete the column free in-situ concrete floors and the small sections of the building envelope. These two zones hinged at a point where a prefabricated proprietary method of scissor-stair construction opened the vertical circulation for the trades below the jump-forms.

A review of the organization of fit-out trades was also necessary, as the unusually small size of the floor plates forbade zoning practically – and economically – of the simultaneous activities of many trades on the same floor. Trade zoning occurred vertically by organizing activities in sections, where finishing and fit-out subcontractors were staggered in time to take vertical chunks of up to 10 floors – rather than floor zones in plan. Additional care was necessary to prevent subcontractors from "stepping on each other's toes" in a very small place, and to work more productively.

Avoidance of fragmentation in the delivery of primary structures allowed controlling quality, cost and risk, while testing innovation and productivity. This approach would not apply to quantitatively smaller, but not less significant parts of the project. Subcontracting of lightweight façades and mechanical services suffered setbacks in quality control and productivity. Contractual fragmentation in this case did not allow the same level of unconventional practice that could be undertaken by a fully in-house team. However, it was also due to the experience gained by these external limitations that the contractor could transfer knowledge from this project and apply more efficient processes of vertical construction to other projects.

The logic of condensing the front-face of construction into a smaller vertical section of the tower was refined technologically in the construction of two other multistory projects in Melbourne, 27 Little Collins Street and 35 Albert Road. The method was also design-developed for another superslim project in the CBD, Collins House, at 464 Collins Street. At 27 Little Collins Street, a unitized curtain wall façade was installed almost in synchrony with the primary concrete structure. The edge of the building was protected by an innovative system of a safety screen equipped with a foldable walkway between the inner face of the screen and the edge beam, while – behind the protective screen – the procedure of installation of the façade followed the usual sequence to launch from the floor. In some instances, this method allowed the curtain wall units to be installed as early as one day after the typical floor slab was poured (see Figure 9).

Melbourne's Logic of Rapid Extrusion

Exceptional slenderness can prompt a radical transformation of the means and methods of high-rise construction. Generally, the established logic of tall building construction consists of layering, through a programmatic sequence of time and place, the work of different trades along a vertical helicoid of activities. Before undertaking superslim projects, this chain-assembly method of construction may need to be reviewed by lead contractors with unconventional project planning practices.

Figure 9. Office building under construction at 27 Little Collins Street, Melbourne. Curtain wall units were installed directly behind safety screens and almost in synchrony with primary structural elements.

The case study of the Phoenix shows that a novel type of process management may need to be considered. The logic of construction of this slender tower can be defined as one of rapid extrusion. The word "extrusion" is meant figuratively, and not simplistically in relation to the form of the building, which in high-rise construction is often characterized by the relentless – but not identical – repetition of a typical floor plan. The process of vertical construction by extrusion is conceptually analogous to that of metal components, where a billet of material is forced under pressure into a condensed throat – the die – which imparts the form to the finished product. In the case of small-footprint skinny towers, the "die" is a condensed zone of working activity under time, cost, and quality pressures, where structure, services and façade trades have to coexist and integrate in shorter space and time than in the conventionally elongated corkscrew organization of large-size skyscrapers.

The implications of slender extrusion expand beyond the mere organization of site activities. The capacity to extrude a project may make it imperative to recur to a hands-on involvement of the head contractor early in the design process. Early contractor involvement trends in high-rise are not a specific novelty of slender towers (Abdelrazaq 2015; Tsang 2014), but other managerial aspects, as used in the construction of the Phoenix, relate specifically to a strategy of construction that was developed ad hoc for slenderness. These aspects were taken with a deliberate outlook for future applications in other projects of similar location, proportion, and intended end use. In this type of project, the lead contractor may have to go beyond generic early-design input to architects and engineers. Re-thinking of the workforce and supply chain with lean procedures, research and development in capital-intensive specialist systems (e.g., a new jump-form patent) may also be combined with low-tech solutions handled by fewer – but multi-skilled or up-skilled – site workers.

The logic of rapid extrusion of slender high-rise construction is the fruit of a component-based mentality and not one of "container-sized" architecture. Therefore, it should not be confused with that of large, modular, off-site factory prefabrication, from which it differs radically. Slender extrusion is managed on-site, assembling rapidly and simply the components of a wind-sturdy shell, preferably in high-strength, high-quality concrete. In 24/7, thriving CBD environments, skinny towers with tight site conditions pose limits of vehicular access, which may prevent large preassembled parts of the building from being transported and handled efficiently. Mega-unitized components may still be used in parts of these buildings, but inner-city superslim construction seems to benefit more from hybrid forms of DfMA (design for manufacturing) or – by analogy – more from IKEA's philosophy of easily assembled flat pack kits. It is less akin to that of factory-made "volumetric modular" construction and long-range international shipping, which may apply more favorably in other circumstances of tall buildings (Wallace et al. 2015; Gardiner 2015).

The logic of extrusion, in the case of the Phoenix Apartments, was triggered by specific circumstances of site, mentality and the economic resources of the local building industry. Yet, these specifics are not unusual or disconnected from global challenges of labor in construction, inner-city residential demands, congestion, historical stratification, and urban density.

The form of these buildings may seem to defy and discourage traditional engineering and entrepreneurial common sense. But once the construction technologies of this typology are expounded dynamically, extreme height in small parcels and niche upmarket demands become a basis to offset the unusual economic pressures, risks and unconventional site management expectations presented to their builders. ■

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