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

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Highlights

- Key challenges and solutions for adopting modular construction for high-rise building are discussed.
- Long span lightweight steel-concrete composite modular system is proposed.
- Slim floor system is proposed to increase module headroom.
- Fast and easy joining technique is developed.
- Stability and robustness analyses of high-rise modular are carried out.

Abstract

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

Introduction

Conventional construction methods that use cast in-situ structural elements and brick walls are still widely used due to relatively low labour cost in some countries. However, the low productivity of such construction methods have impeded economic growth in construction and they are losing their financial advantage with increasing labour costs [1]. At the same time, expanding urban population calls for more high-rise buildings. Coincidentally, a good design practice of high-rise buildings is to embrace simplicity, standardization, repetition, and economy of scale. This renders the high-rise buildings to be intrinsically modular by off-site factory production ([2], [3], [4], [5]).

To overcome these challenges, modular construction has been encouraged in Singapore whereby building modules are constructed off-site before being assembled on-site to form a building. Prefabricated Prefinished Volumetric Construction (PPVC) is a specific type of modular construction where the internal elements of the modules (walls, floors

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and ceilings, mechanical, plumbing and electrical, etc.) are prefabricated before the modules are installed [6]. With the advantages of higher construction speed, productivity and quality control, modular construction has been adopted in many sectors of the building industry, such as residences, hotels and hospitals by several countries over the last 20 years.

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

The idea of modularization is compatible with the design of high-rise buildings which encourages design standardization and repetition. Currently, the cost of modular construction is approximately 15% more than traditional construction unless the benefit from the economy of scale can be fully achieved. By building high-rise, the cost-effectiveness of modular construction can be enhanced due to the increased number of repeated modules with repetitive architectural plan and structural layout. Nonetheless, most of the existing modular construction projects are only constructed up to 20 storeys, as shown in Table 1. This summarizes modular buildings constructed in the past five years. Because of its novel structural form that consists of many inter- and intra-module connections as compared to conventional construction method, the construction industry is not confident and unfamiliar in implementing such technology, hence hindering modular construction from being feasible for high-rise buildings [8,9].

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

Section snippets

Modular construction and its limitations

There are two common types of modular systems with different types of load path. Load bearing wall modules are commonly used in concrete building, in which the concrete walls are used to transfer gravity loads to the foundation, as well as resisting the lateral loads as illustrated in Fig. 2 [10]. The other type of modular system is based on corner supported modules, which are generally made of steel in which the gravity loads are transferred to the slab, then to the edge beams and corner...

Methods to improve efficiency of modular construction

As discussed in Section 2, there are many challenges in high-rise modular construction because its structural form is relatively novel that is different from conventional building. This section proposes solutions to overcome the current limitations of modular construction with the aim of maximizing the construction efficiency and productivity...

Recommendations for future research

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

Conclusions

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

- 1) As the transportation and lifting requirements constraint the weight and size of a module, composite lightweight modular system which incorporates the advantages of both concrete and...

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