International Journal of High-Rise Buildings
September 2017, Vol 6, No 3, 261-269
https://doi.org/10.21022/IJHRB.2017.6.3.261

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Multi-Dimensional Hybrid Design and Construction of Skyscraper Cluster -Innovative Engineering of Raffles City Chongqing-

Aaron J. Wang†

Project Design and Development Management, CapitaLand China Corporate, Shanghai 200001, P. R. China

Abstract

Designed by star architect of Moshes Safdie, Raffles City Chongqing includes a total of 6 mega high-rise towers 250 to 380 m tall, a sky conservatory, a 5-storey high shopping mall and a 3-storey basement car parking. Located at the confluence of the Yangtze and Jailing Rivers, the site for the project is imbued with a significance that is immediately symbolic, both as a sign of Chongqing's important past and as a vivid indicator of the city's thriving present and future. The design for the project to be situated at this gateway takes as its governing idea the image of powerful sails upon the water. The outer facades of the project's eight towers — the transparent surfaces that will face the water to the north — are meant to recall a fleet of ancient Chinese ships, with their huge rectangles of white canvas filled by the wind. This is a 1.13 million m^2 mega scale integrated project of office, retail, hotel, service residence and high-end residence with the transportation hub and traffic circulation at various levels of the project. This paper presents the multi-dimensional hybrid design, engineering and construction of this mega scale project. The innovations and the cutting-edge technology used in this project are introduced and discussed benchmarking the design and construction of the skyscraper cluster in a major city like Chongqing of China.

Keywords: High-rise building cluster, Performance-based design, Damping device, Smart construction

1. Introduction

Located at the confluence of the Yangtze and Jailing Rivers, the site for Raffles City Chongqing is imbued with a significance that is immediately symbolic, both as a sign of Chongqing's important past and as a vivid indicator of the city's thriving present and future. As perhaps the foremost of Chongqing's traditional city gates (the Chaotian Gate, or "gate to heaven"), where emperors carried out the ceremonies of diplomatic greeting, it has long been a historical landmark. As the city's initial dock area on the Yangtze, it also represents the great tradition of the shipping highway, which has stoked this major inland city's development from its beginning and now drives its evolution as one of China's most important modern cities. The site is a true gateway - between eras, and between cultural identities.

The design for the multi-use project to be situated at this gateway takes as its governing idea the image of powerful sails upon the water as shown in Fig. 1. The outer facades of the project's eight towers – the transparent surfaces that will face the water to the north – are meant to recall a fleet of ancient Chinese ships, with their huge rectangles of white canvas filled by the wind. The curved surfaces and the placement of the towers in a prow-like arc create a sense of dynamic motion – implying a great city surging forward, with keen recognition of its commercial heritage on the water. This image is recognizable in its simplicity, yet iconic in its form. In addition to serving as an outward facing gateway symbol, the project also has a strong creative presence as the apex of the city's peninsula. The south facing facades – the inside of the arc of towers – look back to the city in a gently embracing way,



Figure 1. Raffles City Chongqing.

†Corresponding author: Aaron J. Wang
Tel: +86-21-3311-4633, Fax: +86-21-6340-3319
E-mail: aaron.wang@capitaland.com



Figure 2. Multi-dimensional planning and design.

covered by green hanging gardens that meet the ground at a podium roof level that is itself a green amphitheater "park" of gardens, pools, and public circulation. This park-like area is gently sloped to rise to the north, optimizing views to the water through space between the towers – which will house residences, offices, and a hotel and maximizing views of the project itself from the city. This is a 1.13 million m^2 mega scale integrated project of office, retail, hotel, service residence and high-end residence with the transportation hub and traffic circulation at various levels of the project. This paper presents the multi-dimensional hybrid design, engineering and construction of this project. The innovations and the cutting-edge technology used in this project are also introduced and discussed benchmarking the design and construction of the skyscraper cluster in a mega city like Chongqing.

2. Multi-dimensional Design and Planning

The project was carefully planned multi-dimensionally to accommodate the multi-purpose human and vehicle traffic and functions at various levels through the project as shown in Fig. 2. Underneath the park level, the podium consists of five levels of public program (200,000 m^2), including retail and cultural facilities, as well as hubs for land and water transportation (there are 168,000 m^2 devoted to transportation and parking).

Major existing thoroughfares of the city cut into this terminal block from the south, creating further retail "streets" and grand arcades, and providing a strong, fluid overall fusing of the project to the city. Likewise, the harbor-side areas will include not only ferry docking but also landscaped boardwalks, with exterior retail establishments, which will extend public use of the project to the harbor. The flow of transportation into the entire project is carefully but simply executed, at several levels: busses, trains, cars, boats, and ferries all have direct access, with easy circulation to stores and cultural venues, housing, offices, and the hotel.

The two central towers, directly facing the rivers' convergence to the north, are the project's tallest structures (348 meters above flood plain; 80 floors each), with the central axis of the project proceeding back from between them, toward the city. Tucked immediately within the two tallest towers, extending the arc, are four shorter towers (each with 62 floors), across which runs an exterior, connecting garden that hovers 248 meters in the air. In addition to linking these four towers – two of which are office space (196,000 m^2), two of which are residential, and this garden echoes the amphitheater park far below and creates a dramatic viewing platform that optimizes this site's unique views back to the rest of Chongqing. Within the garden level's hull is a full floor of hotel lobby and related functions. Above are the garden and pool amenities. The lobby connects to the uppermost floors of the two tallest twin towers, each of whose highest 34 floors house hotel guestrooms with striking views of Chongqing. The remaining two (freestanding) towers, which complete the prow-like arc of eight, are residential, each 57 floors tall making for a project total of 302,000 m^2 of prime living units. The location and orientation of these two towers allow for maximum views, and for the best use of sunlight. As with the four other "shorter" towers, its south-facing units have hanging gardens that provide a lush green appearance to the city.

3. Hybrid Engineering System

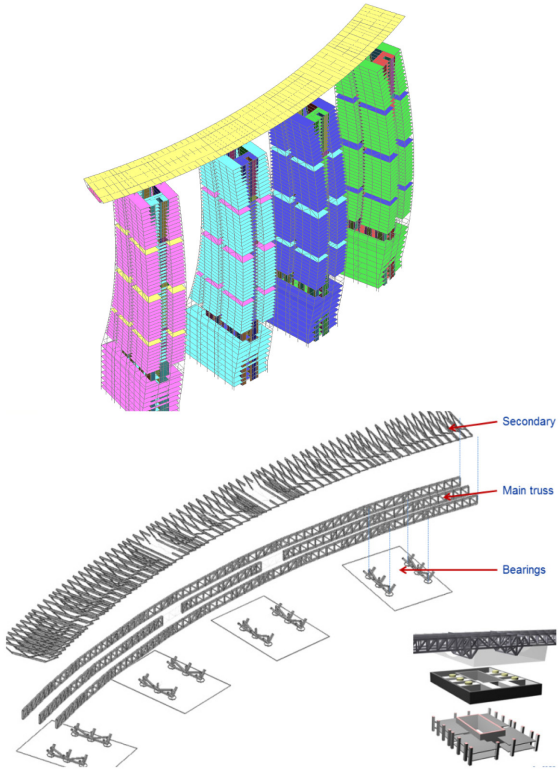
The design and construction of high-rise buildings in China require a rigorous consideration on the impact of

winds and earthquakes. In the current national seismic design codes (MHURD, 2010 and 2011), performance-base design approaches are introduced, which requires the structurally complex building to meet the corresponding stringent requirements under earthquakes with exceeding rates of 63%, 10% and 2-3% respectively. 'Dual system' requirements also need to be met for tall buildings in many circumstances. Wind is another concern for many coastal cities, where the typhoon is normally an issue. The structural engineer normally faces the double challenges of extreme loads from both wind and earthquakes, and needs to keep the overall structural and spatial efficiency in the meantime. Energy dispersing devices, like dampers and isolating bearings, are getting popular in high-rise buildings to enhance the overall structural performance under disastrous loads, instead of putting in additional steel and concrete material and making the overall structure trunky and costly.

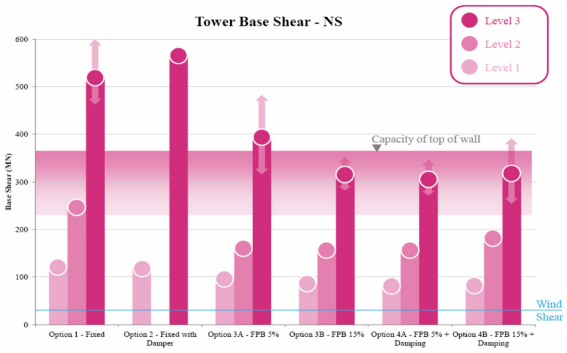
3.1. Intrisic Engineering of Conservatory

The engineering design of conservatory in Raffles City Chongqing allows for the semi-continuous connection between the conservatory decking structures and four of the tower structures below. Fig. 3(a) shows the overall structural configuration. Friction pendulum bearings (FPBs) are adopted between the decking structures and supporting tower structures. A friction coefficient of 5% is chosen after the detailed consultation with the FPB suppliers. FPBs work with viscous dampers and disperse the seismic energy on the occurrence of various levels of earthquakes and relative movement between the tower and the conservatory. The overall engineering design also innovatively utilizes the mass of the conservatory to disperse the seismic energy and control the lateral deflection of the tower structures, as such a 'mass damping' mechanism is facilitated. Fig. 3(b) shows the overall effectiveness of such 'mass damping' effect on the base shear onto towers at various levels of earthquake. Generally, a 35 to 40% of the base shear is reduced due to this innovative configuration between the conservatory and tower structures, which leads to significant saving in building materials in columns and core walls. The SRC structural moment frame together with the core wall system is adopted for all of the 250 m towers in Raffles City Chongqong. The structural design of the project tackled multiple structural irregularities in an Intensity 6.5 seismic zone of Chongqing.

Shaking table tests were conducted on the linked towers to verify the effectiveness of 'mass damping' mechanism and the structural adequacy of the buildings under moderate to extreme earthquakes (Wang 2016). Fig. 4 show the test set-up under various levels of earthquakes, while Fig. 3(b) shows the bearing details adopted in the physical model with a scale of 1:25. The purpose of earthquake simulation shaking table test was to verify the rationality of design calculation and structural provisions, and in the meantime, provided guidance on the necessary



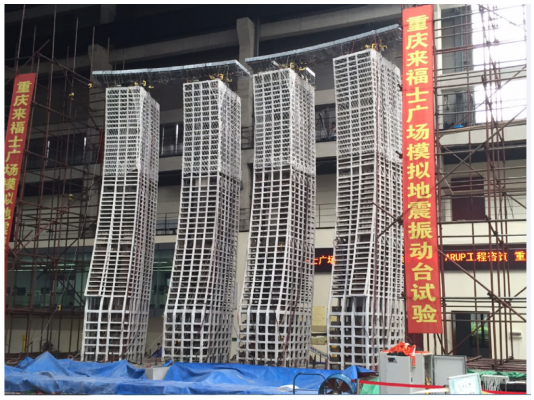
(a) Intrisically engineered conservatory and mass damper



(b) Effectiveness of mass damping

Figure 3. Intrinsically engineering system for conservatory.

further strengthening at particular weak portion spotted. Total self-weight of the model, shaking deck and counterweight is 252 tons. In the view of the load capacities of the shakers, four towers are placed on a total of two shakers generating simultaneous earthquakes from various directions and at multiple magnitudes. The materials with suitable elastic modulus and strength were chosen to produce the physical model. The concrete material was modelled with mortar of the corresponding strength grades, while steel wire was adopted to simulate the steel reinforcements. The encased steel sections were simulated with welded steel angles. The tests were conducted up to a disastrous earthquake with an Intensity 6.5 as per the China



(a) Test set up



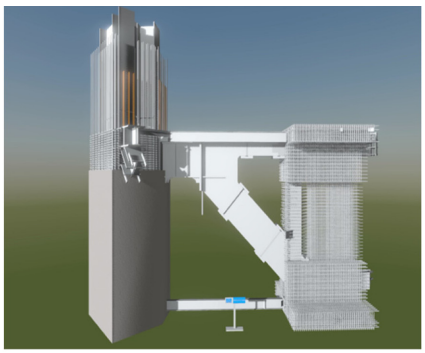
(b) Details of bearings

Figure 4. Shaking table test on linked towers.

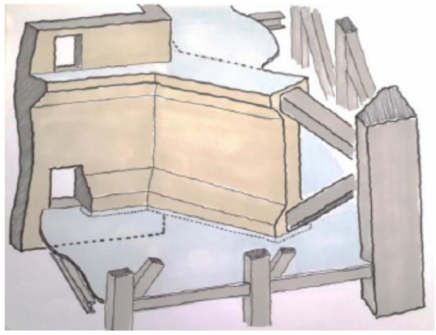
Seismic Code (MHURD, 2010). The structural design of the tower was proved to be generally sound under various levels of earthquakes.

3.2. Damped hybrid outrigger system

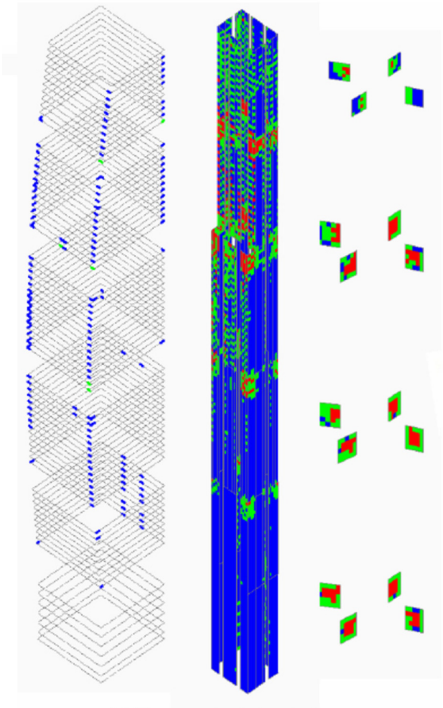
An innovative type of steel-concrete hybrid outrigger truss is also developed in two mega high-rise towers of 380 m tall in Raffles City Chongqing (Wang 2015), in which the steel truss is embedded into the reinforced concrete outrigger wall as shown in Figs. 5(a) and 5(b). Both the steel truss and concrete outrigger wall works compositely to enhance the overall structural performance of the tower structures under extreme loads. Meanwhile, metal dampers were also adopted as a 'fuse' device between the hybrid outrigger and the mega column. The dampers are designed to be 'scarified' and yielded first under moderate to severe earthquakes in order to protect the structural integrity of important structural components of the hybrid outrigger. As such, no brittle failure happens in reinforced concrete portion of the hybrid outrigger system. Fig. 5(c) shows the numerical simulation of the hybrid outrigger system under earthquakes through a general structural engineering software, namely ETABS (2010). The design may allow the contractor to break through the



(a) Hybrid outrigger



(b) Reinforced concrete outrigger wall



(c) Numemrical simulation

Figure 5. Damped hybrid outrigger system.

critical path of the tedious wedding on the steel outrigger truss in the refugee floors, and shoot the core first by leaving the construction joints between the core and the outrigger walls. This helps to shorten the overall construction period of the tower. As per verification tests, the

metal dampers work effectively under Level 2 and Level 3 earthquakes and enhance the overall structural performance. Both finite element modelling and physical component tests were conducted to verify the effectiveness of the hybrid outrigger system. Fig. 6a shows the overall test set up and load deflection curves under cyclic actions. The hybrid outrigger system exhibits sufficient ductility under seismic actions with the effective protection for the 'fuse' devise of low yield steel metal dampers.

3.3. Advanced component and system study

Both the key component and overall system studies were conducted on the proposed hybrid outrigger system, which reveal the detailed structural response under various levels of monotonic and quasi-static cyclic loads as shown in Fig. 6. Various international codes of practice on composite structures and connections are referenced through the test (BSI 2005; AISC 2005; SCI & BCSA 2002). Particular attention was typically given to the following aspects throughout the investigation:

- Load carrying capacity and deformation characteristics;
- Stress distribution and concentration;
- Connection energy dispersion capacities; and
- Typical failure modes and damage locations.

3.3.1. Component test on hybrid outrigger arm

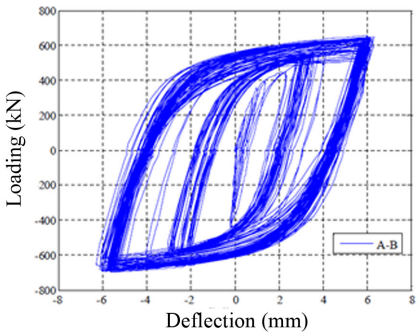
Two specimens of hybrid outrigger arms are tested under monotonic and quasi-static cyclic loads respectively comprising of the steel bracing, the embedded steel section and the concrete outrigger wall. Various key structural responses including load-deformation characteristics, development of stress in steel members and the growth of cracks in concrete were observed and studied. This gives valuable insight into the load deformation characteristics and damage mechanism of the hybrid outrigger arm under both monotonic and quasi-static cyclic loads. No low-yield steel damper was included in this group of physical tests.

3.3.2. System study on hybrid outrigger system with steel damper

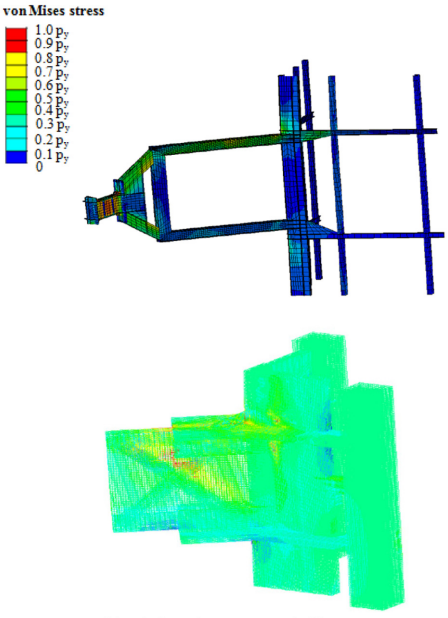
This group of tests studies the performance of the overall hybrid outrigger system including both the low-yield steel damper and the hybrid outrigger arm as connected to the column and the core wall. The load-deformation characteristics under both monotonic and quasi-static cyclic loads were studied and examined in details, and the damage and the failure mode at various key component of the hybrid outrigger system were also investigated.

For the monotonic loading tests, each load step is initially set to be 5% of the estimated overall load carrying capacity, and refined to 2.5% near the failure of the specimen. A pre-load of 15% of the estimated load carrying capacity is applied in order to ensure a directly hard contact of the loading cell and the specimen. For quasi-static





(a) Physical test



(b) Finite element modelling

Figure 6. Study on damped hybrid outrigger system.

cyclic loading tests, the displacement control approach is adopted with the applied displacement of ±Δy/2, ±Δy, ±2Δy, ±3Δy, ±4Δy, ±6Δy, where Δy is the displacement at the first yield of the steel connection. The loading protocol ensures a suitable preloading and sufficient applied

displacements to test the overall ductility of the composite connection in the meantime. The test methods and procedures stated in ASTM (2011) and Lou & Wang (2015) are also considered.

3.3.3. Numerical modelling

Three-dimensional finite element models were also proposed with the incorporation of both geometrical and material non-lieanrities under monotonic loads. A general finite element analyses package, namely ABAQUS (2014), was adopted. As such, the load-deformation characteristics of the outrigger system at both elastic and large deformation plastic stages can be captured properly. Various structural performances were studied and calibrated including load carrying capacities, load-deformation curves and stress distribution and concentration, etc.

Fig. 6(b) is the results of the three-dimensional finite element simulation. It also demonstrated the sufficient ductility at the 'fuse' device while the cracks in the concrete outrigger wall are well controlled even under the action from the severe earthquake. It was also demonstrated that both the steel bracing and concrete outrigger wall are able to work compositely with the low-yield steel damper and exhibits both good load carrying capacities and energy dispersion performance through the test program. The studies provide detailed structural understanding towards such new type of outrigger system. It has the potential to be applied and enhance the overall structural performance of the high-rise structures under extreme levels of loads. More analytical and numerical investigation was also conducted and calibrated for the establishment of the parametric studies and new design rules of such new hybrid outrigger system.

4. Smart Construction and Logistic Management

The construction and logistics management of the project is highly complex and multi-dimensional at various levels of working platforms and vehicle accessibility. The working force was mobilized at various parts of the projects and interfering multi-disciplinarily. Careful planning of the site construction activities, transportation and storage of building materials is the key towards the successful and timely execution of the project up to such scale. Fig. 7 is the different types of digital technology innovatively practiced through the whole process of the project ranging from project scheduling and planning, construction collaboration and interfacing management, site safety and quality management as well as virtual design and construction. As such, both the construction efficiency and accuracy can be achieved.

4.1. Virtual planning and construction

Building information modelling (BIM) was adopted, whose function is further extended to conduct the virtual



Figure 7. Digitized construction management.



Figure 8. Site planning and monitoring.

construction and logistics planning over the site at various phases of the construction. Daily site construction monitoring is conducted through the digital scanning from no-man air-born vehicles (NAVs) on the dynamics of the site logistics and storage layout as shown in Fig. 8. The scanned image is compared with the site planning BIM model

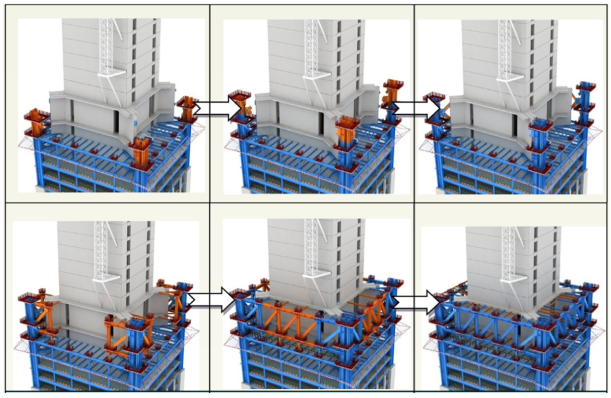


Figure 9. Vertical erection simulation for towers.

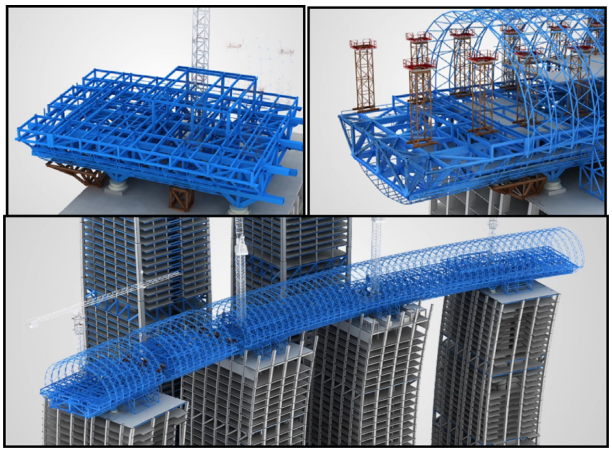


Figure 10. Horizontal construction simulation for conservatory.

for further analyses and any necessary correction action needed.

Virtual construction was also conducted based on the BIM technology on both tower structures and sky conservatory. The key component of structural, M&E, façade works, tower cranes and construction platform were modelled for an accurate simulation of construction cycle and erection speed. In the meantime, any dynamic confliction among the erection of various types of works at limited space can also be detected and avoided through this detailed planning of the construction sequence. Fig. 9 is part of the vertical construction simulation for towers, while Fig. 10 is the horizontal construction and erection simulation of the sky conservatory.

The tailor shape of the project also demands a seamless design and construction integration between the main structure and building façade. This is achieved through the integrated building information modelling and clash detection of integrated structure-façade model. The same integrated model and its geometrical information are used for the fabrication of both the structural steel and façade

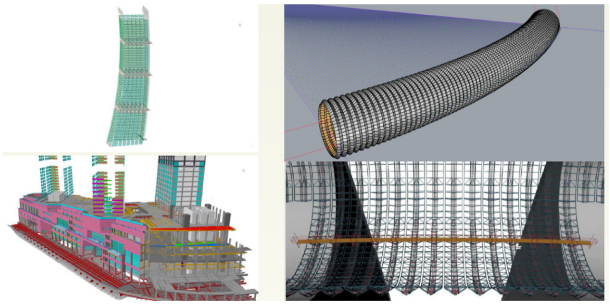


Figure 11. Multi-dimensional façade-structure intergration.



Figure 12. As-built scanning.

panels. Fig. 11 shows such an integrated model. As such, a higher level of accuracy can be achieved during the on-site erection of both structural and façade works.

4.2. As-built information management

It is important to manage the as-built information of various parts of works, which may impact the accuracy and quality of the sequential construction works. As such, three-dimensional scanning technology was adopted in Raffles City Chongqing, which scan the geometrical information for finished structural and steel works and incorporated into the established building information models. As such, the deviation of the civil construction from the designed geometry can be tracked timely, and any necessary correction works can be conducted to control both the headroom and installation accuracy of the sequential works.

Fig. 12 shows one of the typical practices of such technology. It greatly enhances the re-measurement efficiency as compared with the manual measurement practice, and is able to reflect the construction and erection accuracy data on a more real time base.

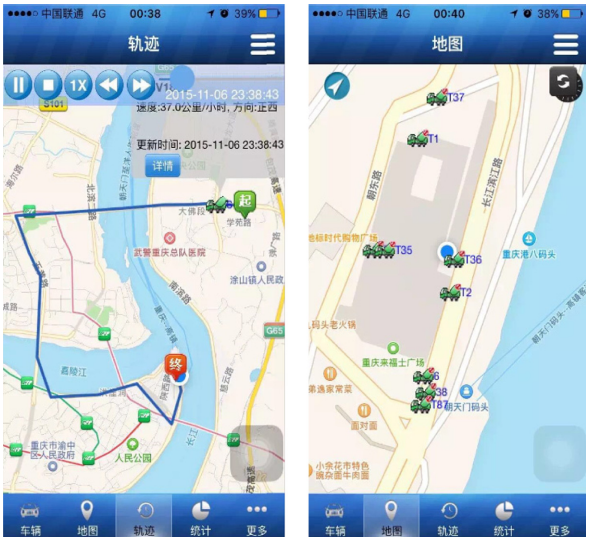


Figure 13. Building material and logitics tracking system.

4.3. Building material and logistic tracking system

For a typical hybrid type project, the timely and quality delivery of major construction materials is important for site planning, which potentially impacts the overall construction progress and building quality. This becomes especially critical for those materials whose construction and installation are in the construction critical path. These materials include, but not limited, to concrete, steel works, façade panels, etc. For concrete material, there is always a risk of over-consolidation due to the exceeding transportation time, which shall be prohibited from the site. As such, the overall logistics management of a project shall extend beyond the site border and be through the whole logistic chain of the major building materials preferably on a real time base, so that the overall delivery and transportation process can be properly tracked and managed. A real-time monitoring and tracking system was developed through on Raffles City Chongqing based on a modern GPS technology, which allow for a real time planning and tracking of the procurement and transportation of major building materials. Fig. 13 shows the typical interface of such system through a mobile device.

4.4. Quality and safety management system

There is normally large amount of drawings and specifications of various disciples and versions in complex commercial projects. In many circumstances, linkage among design, specifications, construction and quality control is not tight enough to facilitate an accurate and quality site implementation. In addition, it is normally time consuming to report on construction defect and recertification measures, which possibly delays the necessary recertification works before the cover up. Hence, it is highly beneficial to use the digitalized construction inspection and quality control tool with detailed check-list



Figure 14. Construction quality monitoring.

on detailed quality control points for each building components to streamline and achieve the effectiveness and efficiency on the process quality and safety control of site works. With such quality monitoring system in place in Raffles City Chongqing as shown in Fig. 14, a stringent and timely follow up on site quality issues is able to be achieved.

In the meantime, site safety simulation and evacuation were also conducted at various simulated phases of the project as shown in Fig. 14. As such safety measures, signage and training were conducted more specifically for various regions and various stages of the project per the different complex site conditions.

5. Conclusions

This paper presents the multi-dimensional hybrid design, engineering and construction of Raffles City Chongqing. The innovations and the cutting-edge technology used in this project are also introduced and discussed benchmarking the design and construction of the skyscraper cluster in a mega city like Chongqing. The following conclusions is reached:

5.1. Multi-dimensional planning and design

The planning and design of modern integrated development project demands a high level of integration of various commercial functions, leisure and recreation, various

ways of transportation to the destination. This require multi-dimensional planning and design of the project to accommodate the circulation and functions at multiple levels around the properties.

5.2. Hybrid engineering system

The engineering design of such project demands the multiple key functions of load bearing, seismic and wind proof, and various hazard and risk mitigation. The hybrid and intrinsic engineering system shall be adopted with the aid of the modern and numerical engineering analyses technology. As such, a higher level of efficiency and cost effectiveness can be achieve.

5.3. Smart construction and logistic management

The proper construction planning and accessibility management is critical for the construction of such mega scale project at the city centre of congested spaces. The scheduling, site planning and material procurement and transportation shall be carefully crafted with the aid of modern digital technology. In the meantime, the digital technology also facilitate the engineer and manager to conduct a more real time tracking on the performance of various construction activities. As such, more timely correction and remediation action can be taken through the execution of the project.

References

ABAQUS (2014). *User's Manual*, Version 6.14., Hibbitt, Karlsson and Sorensen, Inc.

American Institute of Steel Construction (2005). *ANSI/AISC 360-05: Specification for Structural Steel Buildings*, AISC.

ASTM (2011). *E2126-11: Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings*, ASTM.

British Standards Institution (BSI) (2005). *Eurocode 3: Design of Steel Structures, Part 1.8: Design of Joints*, European Committee for Standardization.

China Academy of Building Research (CABR) (1997). *Specification of Test Methods for Earthquake Resistant Building*, CABR.

ETABS (2010). *User's Manual*, Computers and Structures, Inc.

Lou, G. B. and Wang, A. J. (2015). "Studies into a high performance composite connection for high-rise buildings." *Steel and Composite Structures*, 19(4), pp. 789-809.

The Ministry of Housing and Urban-Rural Development (MHURD) (2010). *Code for Seismic Design of Buildings: GB50011-2010*.

The Ministry of Housing and Urban-Rural Development (MHURD) (2011). *Technical Specification for Concrete Structures of Tall Buildings: JGJ3-2010.*

The Steel Construction Institute (SCI) and the British Constructional Steelwork Association Limited (BCSA) (2002). *Joints in Steel Construction*, the Steel Construction Institute.

Wang, A. J. (2016). "The evolution of modern mega buildings in China - innovation and overall sustainability." *ICE Proceedings of Civil Engineering*, pp 113-120.

Wang, A. J. (2015). "Re-engineering composite connections for a higher construction and cost Effectiveness." *Proceedings of 11th International Conference on Advances in Steel and Concrete Composite Structures*, pp. 538-543, Tsinghua University, Beijing, China.

Wang, A. J. (2017) "Raffles City Hangzhou China - the engineering of a 'vertical city' of vibrant waves-." *International Journal of High-rise Buildings*, 6(1), pp. 33-47.