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The Evolution of Seismic Engineering and Design of Ultra Tall Buildings in China Innovations and Sustainability

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Abstract

With the booming of construction and property industries in China, the demand for high-rises and mega-scale buildings with more integrated building functions, open- and tailor-shaped outlooks, better connections to municipal infrastructures, and higher grades of building importance has been increasing in the past two decades. The seismic design and engineering of such modern mega-buildings face engineering challenges such as hazard mitigation of extreme actions and surroundings, integrated structural frameworks and building skins, complex connections, and overall construction efficiency. It is the work of a new generation of civil and structural engineers to enhance engineering efficiency and achieve overall engineering, environmental, and economical effectiveness for these high-rise projects. This paper elaborates the above topics through case studies on the design and construction of four such developments in China. Some rethinking is conducted on evolution in modern seismic engineering and design through innovation to achieve an acceptable level of overall sustainability and building effectiveness.

Keywords: Seismic engineering, Mega projects, Composite structures, Performance-base analysis, Construction, Sustainability

1. Introduction

The booming of construction and property industries in China increasingly demands high-rise and mega scale buildings in the past two decades. The main features of such mega buildings include:

- Higher grades of building importance and hazard mitigation;
- Bigger in scale with more integrated building functions and controllable carbon footprint;
- Open and tailor-shaped building outlook with a better involvement with the community; and
- More seamless connection to municipal infrastructures facilitating population circulations.

The design and construction such modern mega buildings face the engineering challenges in hazard mitigation of extreme actions and surroundings, integrated structural frameworks and building skins, complex connection and overall constructional efficiency. It is the work of the new generation of civil and structural engineers to add value, enhance overall engineering efficiency and achieve overall environmental and cost effectiveness towards the project.

This paper elaborates the above topics through the case studies on the design and construction of four of such developments in China. Some rethinking is conducted on evolution in modern seismic engineering and design through innovation and to achieve an overall sustainability and structural effectiveness.

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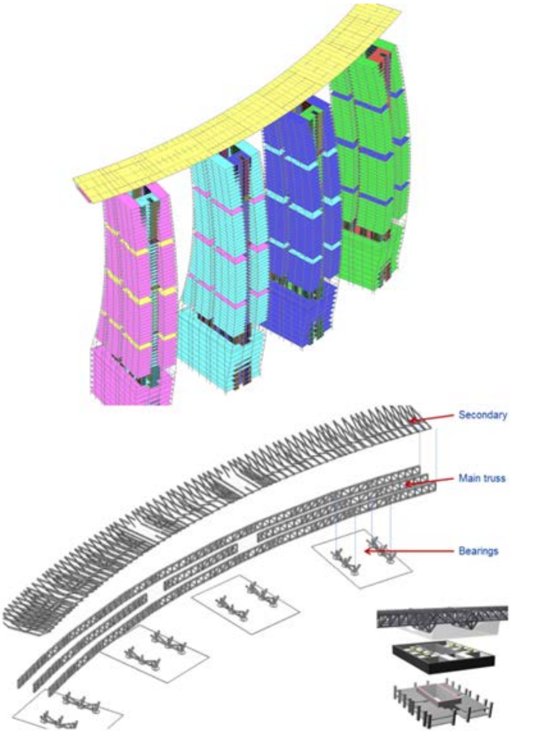
2. Hazard Mitigation - Innovative Engineering against Extreme

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, 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.

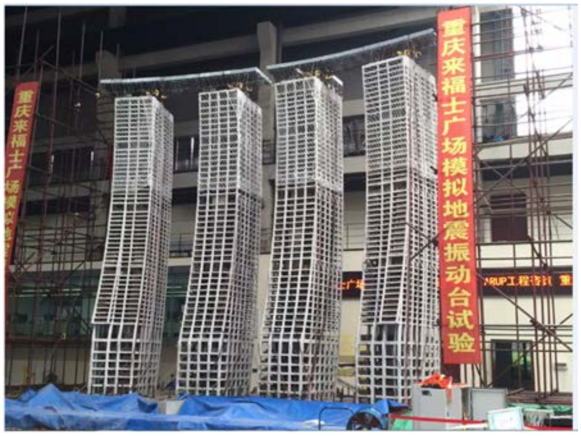
Designed by a star architect of Moshes Safdie, Raffles City Chongqing (RCCQ) includes a total of 6 mega high-rise towers 250 to 370 m tall including office, hotel, residential and service apartments, a sky conservatory, a 4-storey high shopping mall and a 4-storey basement car



a) Intrinsical observatory and mass damper

b) Effectiveness of mass damping

Figure 1. Intrinsically engineered mass damping.



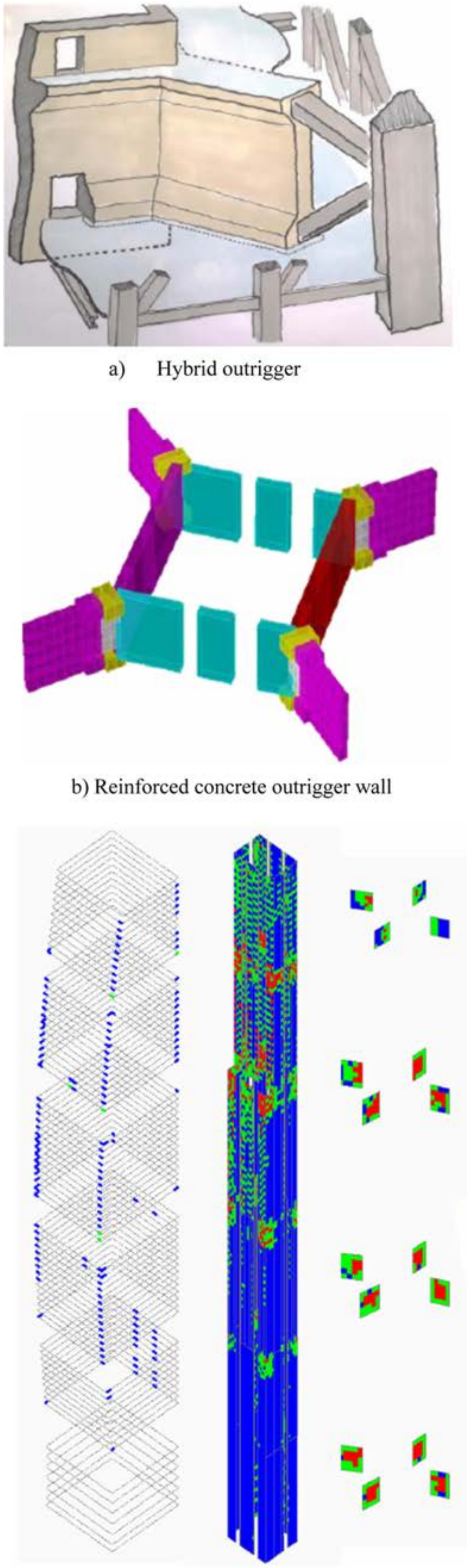
b) Details of bearings

Figure 2. Shaking table tests on RCCQ.

parking. The overall CFA of the project is over 1 million square meters. The engineering design of conservatory in RCCQ allows for the semi-continuous connection between the conservatory decking structures and four of the tower structures below. Fig. 1(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 utilize 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. 1(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 RCCQ. 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. Fig. 2 show the test set-up under various levels of earthquakes, while Fig. 2(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 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 Seismic Code (MHURD, 2010). The structural design of the tower was proved to be generally sound under various levels of earthquakes.

An innovative type of steel-concrete hybrid outrigger truss is also developed in two mega high-rise towers of 370 m tall in RCCQ (Wang, 2015), in which the steel truss is embedded into the reinforced concrete outrigger wall as shown in Figs. 3(a) and 3(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, not brittle failure happens in reinforced concrete portion of the hybrid outrigger system. Fig. 3(c) shows the numerical simulation of the hybrid outrigger system under earthquakes. The design may allow the contractor to break through the 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. 4(a) 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. Fig. 4(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.



a) Hybrid outrigger

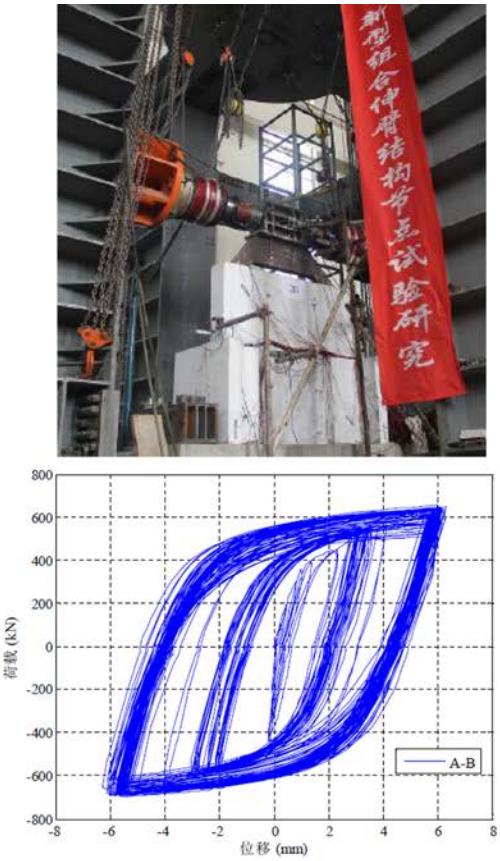
b) Reinforced concrete outrigger wall

c) Numerical simulation

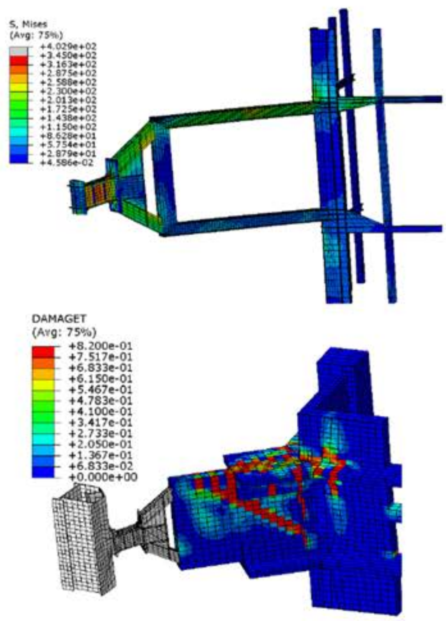
Figure 3. Hybrid outrigger system.

3. Value Engineering - An Overall Effectiveness

Value engineering (VE) is a systematic method to imp-



a) Physical tests



b) Finite element modelling

Figure 4. Study on hybrid outrigger.

rove the ‘value’ of goods or products and services by using an examination of function. Value, as defined, is the ratio of function to cost or material used. Value can therefore be increased by either improving the function or reducing the cost or material used (Cooper & Slagmulder, 1997). For the value engineering in a building project, it does not simply mean a cost reduction, but also an enhancement in building performance and construction productivity from a whole life circle point of view.

Raffles City Hangzhou (RCH) is located in the central business district of Hangzhou, China, and composed of two 60-storey 250 m tall super high-rise twisting towers and a commercial podium and 3-storey basement car parking. The overall construction floor area of the project is 390,000 m^2. In RCH, composite moment frame plus concrete core structural system is adopted for the 250 m tall tower structures. A total of three outer frame forms were studied as follows:

Option 1: Steel floor beams together with concrete filled steel tubular (CFT) columns;

Option 2: Concrete floor beams together with steel reinforced concrete (SRC) columns, and

Option 3: Steel reinforced concrete (SRC) beams together with CFT columns.

Cost comparison and work breakdown analyses were conducted for a typical tower floor. The results are shown in Tables 1 and 2 respectively. It was concluded that that Option 3 of SRC floors beams together with CFT columns share a similar low construction cost as the reinforced concrete dominant Option 2. While overall construction cycle of Option 3 is much lower by breaking through the critical path of column construction with permanent formworks of steel tubular columns. The construction cycle per typical floor is approximated to be 5 days as shown in Table 2.

Thus, Option 3 was selected to be the outer moment frame of the tower structures with a relatively low cost, controllable constructability and reasonable building functions. Fig. 5(a) shows the structural frameworks of the tower structures. Main structure has been topped up last year, and Fig. 6 shows the site construction of the main structure. It was demonstrated that 5-day-cycle is achievable with the adopted structural form.

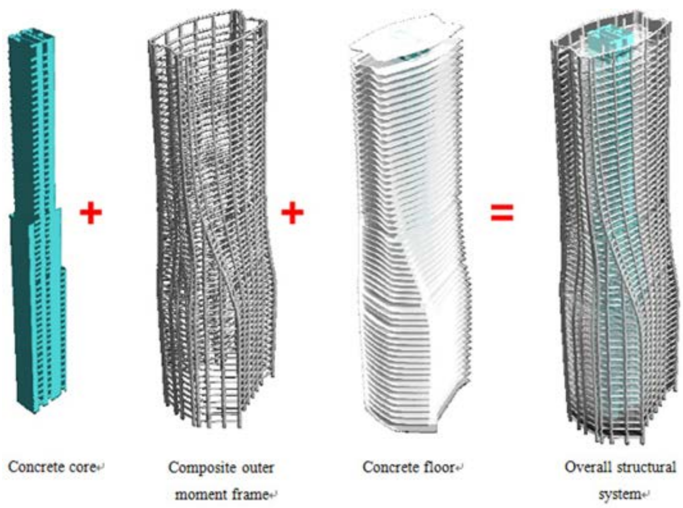
Performance base seismic design was adopted to analyze the structure, including both static and dynamic elasto-plastic analyses under various levels of wind, earthquake and gravity loads. Structural analysis software of both ETABS (2010) and ABAQUS (2004) were adopted to conduct the global structural analysis and counter-check the results with each other. In the global structural models, beam-column elements were adopted to simulate the moment frame and bracings of the structures, while 4-noded shell elements were adopted to simulate the structural behaviour of shear walls and slabs. The equivalent strength and stiffness were adopted to consider the contribution of the steel section to the overall stiffness and strength of composite columns and bracings. In the elasto-plastic nonlinear simulation, the solution procedure requires the full load to be applied in a series of small increments so that

Table 1. Cost comparison on structural schemes of RCH Tower

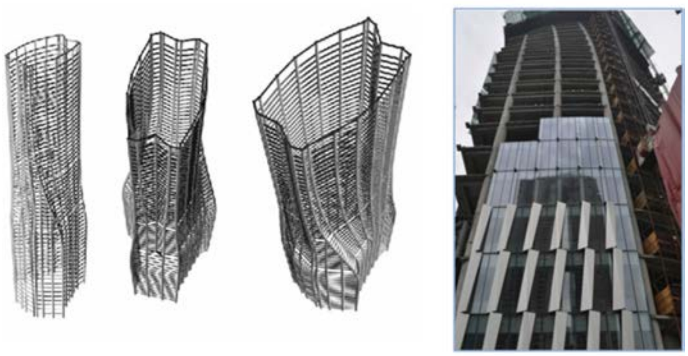
Item	Option 1: Steel floor beams + CFT columns	Option 2: RC floor beams + SRC columns	Option 3: SRC floor beams + CFT columns
Concrete (m^3/m^2)	0.54	0.97	0.97
Rebar tonnage (kg/m^2)	110	117	102
Steel tonnage (kg/m^2)	118	62	68
Formwork (m^2/m^2)	0.97	2.1	2.1
Profiled steel decking (m^2/m^2)	0.82	-	-
Overall cost (%)	149%	100%	105%

Table 2. Work breakdown analysis of a typical floor of RCH Tower

Option 1: Steel floor beams + CFT columns		Option 2: RC floor beams + SRC columns		Option 3: SRC floor beams + CFT columns	
Work breakdown	Days	Work breakdown	Days	Work breakdown	Days
Erection of steel tubular columns	0.5	Circular column formwork	1	Erection of steel tubular columns	0.5
Erection of edge beams	0.5	Erection of column rebars	1	Erection of edge beams	0.5
Erection of floor steel beams	1.5	Erection of edge beams	0.5	Erection of floor steel beams	1.5
Rebar erection in slab and walls	1.5	Erection of floor steel beams	1.5	Rebar erection in slab and walls	1.5
Concrete pouring	1.0	Rebar erection in slab and walls	1.5	Concrete pouring	1.0
		Concrete pouring	1.0		
Total	5.0	Total	6.5	Total	5.0



(a) Tower structural system



(b) Integrated building skin

Figure 5. Raffles City Hangzhou.

Figure 6. Construction of RCH.

the solutions may follow the load-deflection closely. A value of 5% is recommended as the maximum plastic strain increment in each incremental load. In order to accurately model the large deformation at critical locations after steel yielding as well as local concrete crushing and splitting, both material and geometrical non-linearities were incorporated into the finite element model. As this is a highly nonlinear problem, the solution is obtained through a number of equilibrium interactions for each load step. This is accomplished by an arch-length procedure in which the nodal displacements, the out-of-balance forces and the tangent stiffness matrix of the structure are updated after each equilibrium interaction. A force-based convergence criterion is adopted which requires the imbalance force is less than 0.5% of the average applied force in each equilibrium interaction.

Figs. 7(a) and 7(b) shows the comparison of the analyzed results according to both ETABS (2010) and ABAQUS (2004) in a moderate earthquake. It was demonstrated that both of the software gives quite similar results in both inter-floor drifting and base shear of the building. More detailed level of local numerical models were also set up in some particular portions like major cantilevers and transfer truss, prominent block and linking bridges. The reaction forces at the support position were derived from the results of the global analyses at various levels of limit states. Three-dimension finite element models built up with solid elements were also set up to study the structural performance of complex steel and composite joints as shown in Fig. 8(b).

4. Joints - Re-Engineering against Complexity

The detailing of joints is always a frontier to conquer in the design of modern high-rise composite buildings. The rigidity and ductility requirements of composite joints are covered in various prevailing design codes (AISC, 2005; Brockenbrough & Merritt, 2006; BSI, 2005; MHURD,

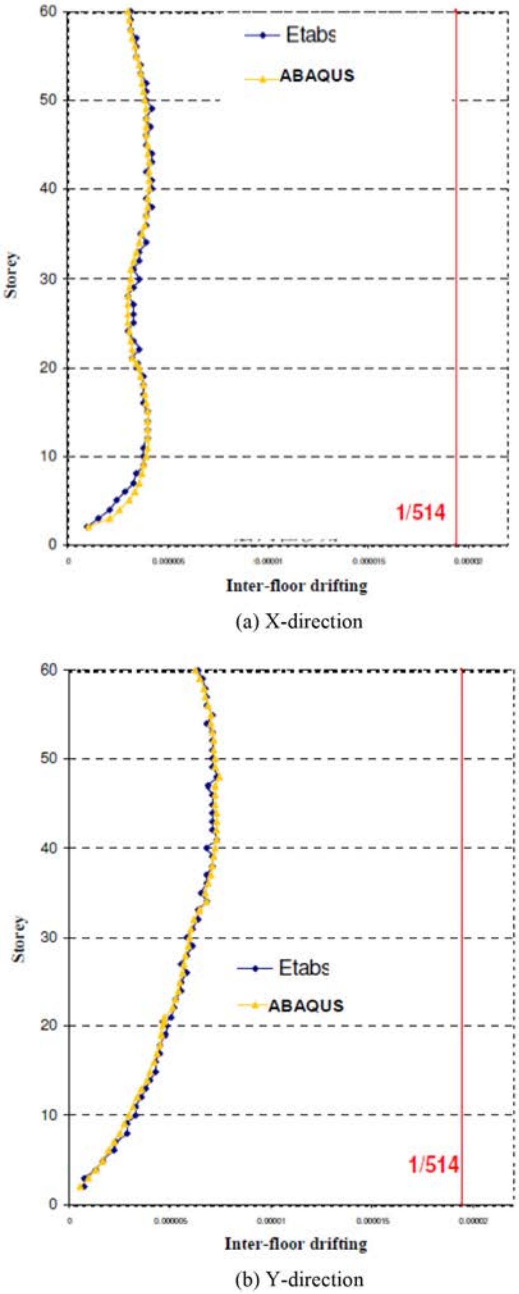
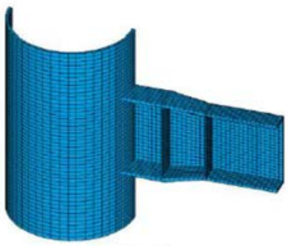


Figure 7. Inter-floor drifting of RCH Towers.

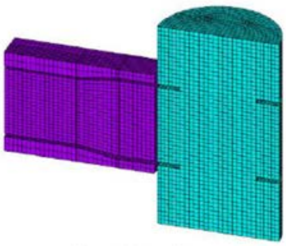
2011; SCI & BCSA, 2002).

In RCH, the structural design of the composite connection between CFT columns and SRC beams need to safeguard the overall structural stability through the fully rigid connections and avoid scarifying any tailored space in the meantime. The conventional ring beam type composite connection is regarded to be bulky and not suitable because of its inference with the façade erection and interior decoration. An innovative and high performance corbel type composite connection is proposed with a minimum intrusion into the interior space to achieve the fully rigid

(a) Test set-up



Steel section



Concrete section

(b) Finite element model

Figure 8. Connection test and numerical simulation.

connection (Lou & Wang 2015; Wang 2015). The proposed corbel type composite joints include the following key components as shown in Fig. 8:

- The corbel and ring stiffener as butt welded to the CFT column:

In order to ensure a full strength rigid connection, the I-section corbel is enlarged and stiffened together with a ring stiffener as welded inside the steel tube, so that the overall rigidity and load carrying capacity of the connection is not less than that of a typical SRC beam section.

- The tapered section from the corbel to the steel beam:

In order to ensure a smooth loading and stress transfer from the corbel in the joint region to the ordinary SRC beam, a tapered steel section is proposed with a slope of 1:6.

- The steel section in the SRC beam:

The ordinary I-steel section in the composite SRC beam is fully connected to the outer edge of the corbel through full bolted joints on both flanges and webs.

- Lapped reinforcement bars:

All the longitudinal reinforcements are lapped around the flanges of the steel corbel, so that both the loads and stress can be transferred from the longitudinal main reinforcements onto the corbel in the connection region.

Physical tests under both static and cyclic loads were conducted to investigate the load carrying capacities and deformation characteristics of this new type of composite connection according to both ASTM (2011) and CABR (1997). Fig. 8(a) shows the overall set up of the tests. A variety of structural responses are examined in detail, including load-deformation characteristics, the development of sectional direct and shear strains, and the history of cumulative plastic deformation and energy. A three-dimensional finite element model built up with solid elements was also proposed and carefully calibrated incorporating the material, boundary and geometrical non-linearities as shown in Fig. 8(b). Both the experimental and numerical studies demonstrate the high rigidity, strength and rotation capacities of the corbel type composite connections, and give detailed structural understanding for engineering design and practice.

Figs. 9(a) and 9(b) present the results of the monotonic tests on Specimens SP1 and SP2, while Fig. 10 presents a typical failure mode. A close observation on the strain development also shows that the direct tensile strain at the top flange is 30 to 50% higher than the compressive strain of the bottom flanges due to the contribution of the concrete material. It is noted that the shear strain in the web is significantly smaller than the strain in the flange, which is just above the yield strain. This is preferred for a high-rise building in a seismic sensitive region like Hangzhou, where the Project located. The quasi-static cyclic loading tests were conducted on both Specimens SP3 and SP4. Figs. 9(c) and 9(d) present the load-deflection and moment-rotation curves of Specimens SP3 and SP4. The cumulative plastic deformations of both Specimens SP3 and SP4 are 0.3 and 0.24 rad respectively, which are corresponding to 88 and 80 times the first yield rotation of the composite connections. This, again, demonstrates the high ductility and energy absorbing capacities of the corbel type composite connections.

To study the structural behaviour of the corbel type composite connection, a generalized nonlinear three-dimensional finite element model was set up using the commercial finite element package ANSYS 12.1 (2011). The meshes of the finite element model are shown in Fig. 8(b). In order to simplify the problem and save computational time, only half of the specimen was modelled. The finite element simulation gives a quite close prediction of the

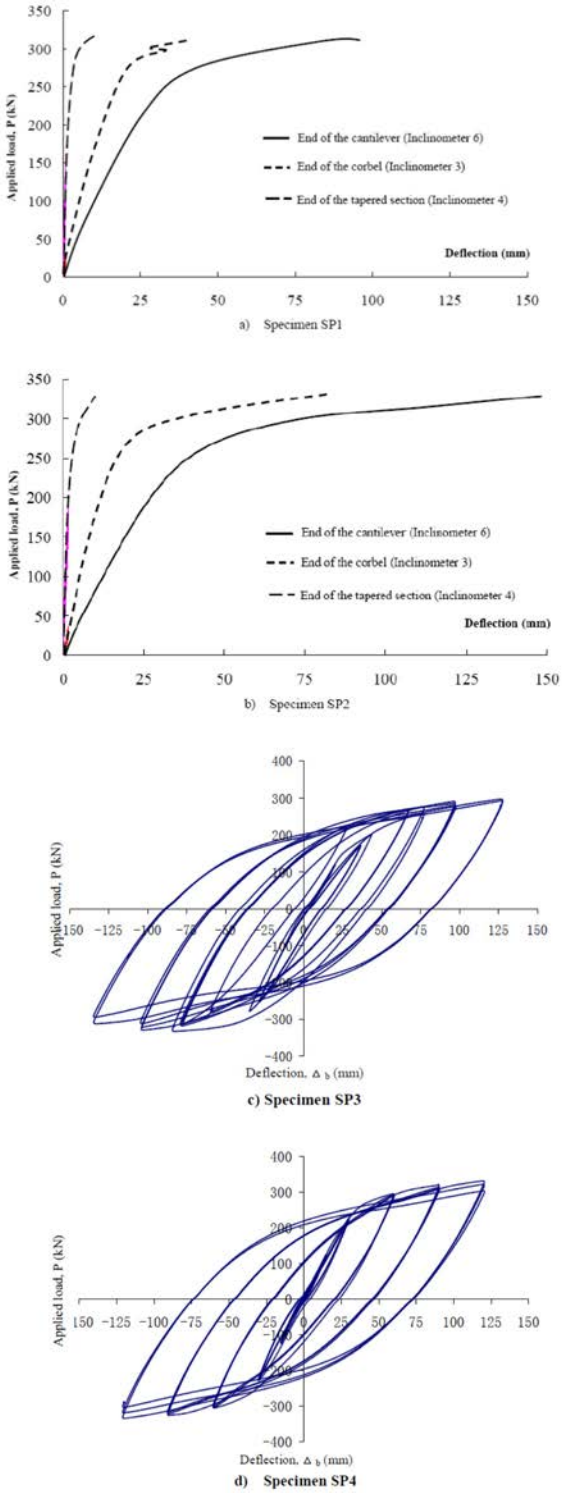


Figure 9. Load-deflection curves.

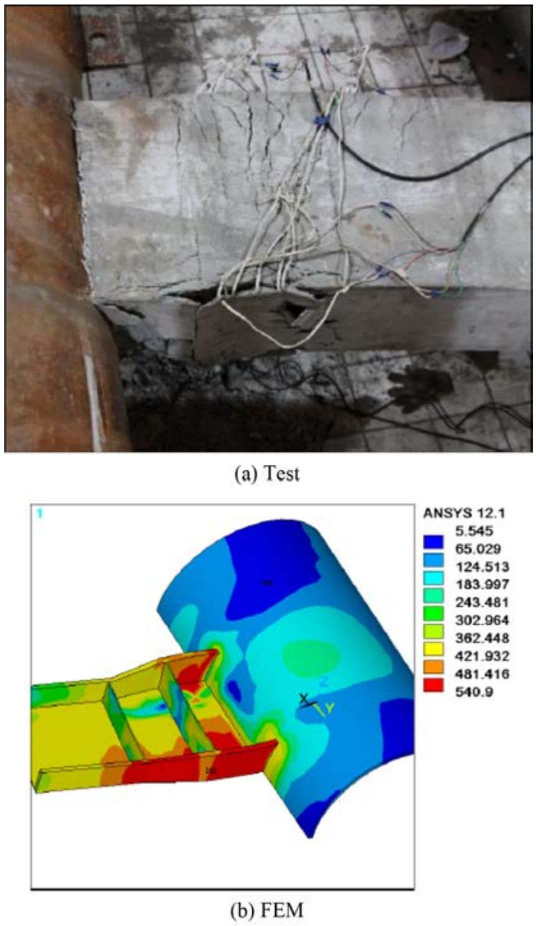


Figure 10. Typical failure mode.

load-deformation characteristics in the connection regions, which is demonstrated through the comparison of the load-deformation curves at the end of the connection corbel (Lou & Wang, 2015; Wang 2015). Fig. 10 shows the typical failure models of the corbel type composite joints from both physical tests and numerical simulation. As such, the corbel type composite joint was verified to be of high strength, rigidity and ductility and suitable for highrise buildings in seismic sensitive regions.

5. Digitized Engineering - Integrated with Building Skin

The advancement of the modern computerised design tools allow the designer to break though the barrier of conventional modular design, and work on three-dimensional platform. Nowadays, more free-form tailor-shape building skins are able to be achieved in a more creative way. Structural engineer shall equip themselves with three-dimensional design technology, and produce structural frameworks well suits the building skins. As shown in Fig. 5(b) for RCH, structural members are tailored to support the facade outer skin, and form the modern outlook of the building. Both the structural engineer and main contractor work collaboratively on a three-dimensional platform to establish the setting out information on site.

Raffles City Chengdu (RCC) is featured with its usage of high-strength light-colour off-form concrete in its outer

Figure 11. Raffles City Chengdu.

frame, which forms part of the facade system together with the window wall as shown in Fig. 11. This project is composed of five 110 m tailor-made high-rise towers including office spaces, hotels and service apartments and a 4-storey shopping mall plus a 4-storey basement car parking. This project has been completed and opens to public since 2012. The design greatly reduced the glass coverage surface areas, leading to significant savings the facade cost. Despite of the relatively high unit cost for off-form concrete as compared with the ordinary concrete, the overall cost effectiveness was still achieved on adopting such philosophy of intrinsic design (Wang & Hong, 2015). Several trial mixes were conducted in the tendering and construction stages to ensure the finish and concrete colour meet the architectural design intent, and the mechanical properties meet the engineering design requirements. In addition, durability tests such as chloride penetration tests and concrete curing tests were also done to ensure an alkaline dominant concrete mixture with the acceptable crack width.

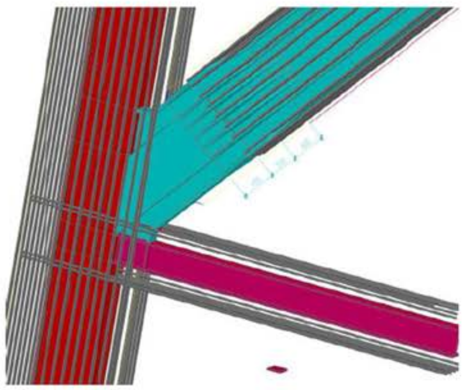
This project also faced another challenge of composite joints among SRC columns, beams and diagonals, leading to especial complexity and possible confliction between the reinforcement and steel sections. Both construction mock-ups and a three-dimensional computer tool are adopted to assess the erectability allowing for reasonable construction tolerance and work space in the meantime. Stiffener and gusset plates were adopted to transfer the loading from the reinforcement into the joint region without scarifying the structural continuity and rigidity. Fig. 12 shows the construction mock-up and computer detailing visual model.

Building Information Modelling (BIM) was adopted in both RCCQ and RCH to sort out the complex building shapes and possible confliction at especially complex locations like basement, mechanical floors, cores and conservatory. A BIM protocol was set up among various design parties and contractor to streamline the management procedures, and a BIM manager was employed to adminis-

Before optimization

After optimization

(a) Construction mock-up



(b) Three-dimensional detailing

Figure 12. Detailing of composite joints.

trate the daily model operation and design coordination. The civil and structural BIM model was issued to the tenderers as part of the tender documents to assess the possi-

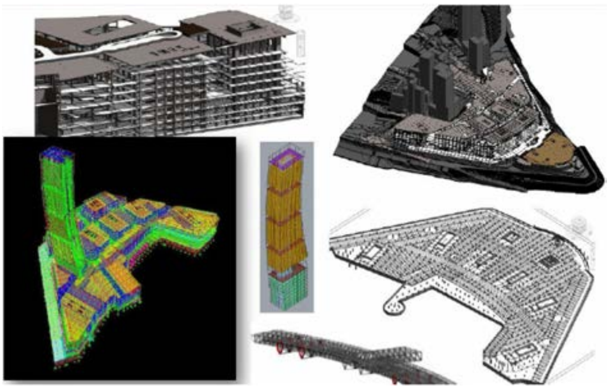


Figure 13. BIM of Raffles City Chongqing.

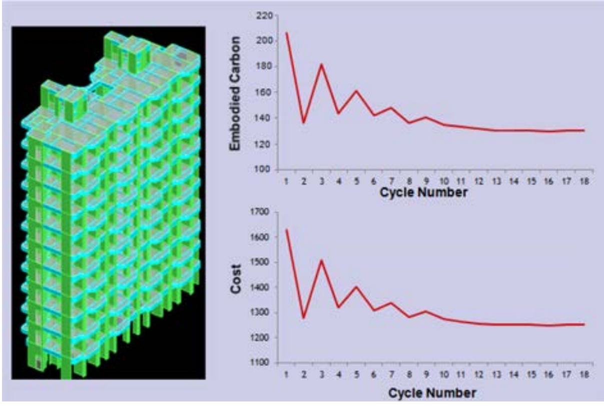


Figure 14. Numerical optimization of embodied carbon and construction cost.

ble major dynamic confliction in the complex site logistics, like installation of mega steel works and facade panels, etc. Fig. 13 is the structural BIM models in various major components of the project.

6. Retrofitting Engineering - An Overall Sustainability

All the above-introduced aspects and technologies will facilitated a more efficient and better integrated engineering design and construction. This will contribute positively to the overall sustainability of the building construction and development through the reduced usage of building materials and less tedious effort and energy consumption in site implementation. As such, the overall carbon footprint throughout the building development can be reduced accordingly. Some of the key issues need to be considered through the engineering of the mega projects include:

- Controllable building footprint and aspect ratio;
- A proper consideration of composition of concrete, reinforcement and steel materials to achieve a optimal embodied carbon consumption;
- Possible utilization of seismic/wind energy dispersing devices to prevent the over-sizing structural members and enhance the overall engineering efficiency;
- Consideration of carbon footprint from material supply and transportation, especially for some precast concrete and structural steel components; and
- To maximize the reusage of existing buildings and structural frameworks through rigorous engineering approach in a brownfield development.

Fig. 14 shows a computer program being developed to carry out the structural design optimization towards the most cost and carbon effective structural layouts on typical residential blocks. Multiple constrains on structural member sizes and rebar ratios can be assigned as input condition, and the computer program, as linked with a standardized structural analysis software, will interact and reach a dual optimized structural layout toward both cost and carbon effectiveness.

The maximized possible reuse of the existing structural frame works is always a priority in a browfield development. This not only leads to cost effective design, but is also a carbon effective engineering solution. Necessary alternation and strengthening works need to be conducted to fit the newly defined building functions and general layout plans. For the steel frameworks, necessary de-rusting and corrosion and fire proof need to be conducted. This project, namely International Trade Centre (ITC) as shown in Fig. 15, is such a type of bownfield development that CapitaLand did in the downtown area of Tainjin. The new design include a total of one 250 m tall steel hotel towers, 2 composite office towers of 180 m tall, a 5 storey commercial podium and 3 storey basement. The engineering and construction of the project is on an unfinished steel skeleton with a half-finished basement concrete works. The re-development including the reusage of the large portion of existing structural frameworks and the associated strengthening works. Rigorous de-rusting works was conducted with the set up of visual mock-ups regarding finished surfaces. The strengthening works involve both enlarged member sizes on existing steel beams and columns and concrete works in basement. Both metal and viscous dampers were designed and installed to ensure the overall structural stability and conformability under wind and seismic actions.

7. Conclusions

This paper elaborates the evolution in modern seismic engineering and design of mega highrise buildings in China through innovation and to achieve an overall sustainability and effectiveness. Some challenges faced by modern civil and structural engineers are addressed including hazard mitigation of extreme actions and surroundings, integrated structural frameworks and building skins, complex con-

(a) Before de-rusting (b) After de-rusting

(c) Protection to the surroundings (d) Project imagine

Figure 15. International Trade Centre (ITC).

nection and overall constructional and environmental efficiency. The following conclusions are reached through the above elaboration and rethinking:

- The structural engineer needs to face the double challenges of extreme loads from both earthquake and wind, and ensure 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 structure trunky and costly.
- The detailing of joints is always a frontier to conquer during the design of modern high-rise composite buildings. The rigidity and ductility requirements of composite joints shall be met. Three-dimensional computer tools, verification tests and construction mock-up shall be done for some complex composite joints.
- Nowadays, free-form tailor-shape building skins are able to be achieved in a more creative way. Structural engineer shall equip themselves with three-dimensional digital technology, and produce structural frameworks well suits the building skins.
- From an overall construction and environmental effectiveness point of view, an efficient engineering and design aim for the enhancement in building performance and construction productivity from a whole life circle point of view. Structural engineers shall creating value through innovations and rigorous engineering approaches.
- All the above-introduced aspects and technologies will facilitated a more efficient and better intrinsic engineering design and construction. This will contribute positively to the overall sustainability of the building construction and development through the reduced usage of building materials and less tedious effort and energy consumption in site implementation. As

such, the overall carbon footprint throughout the building development can be reduced accordingly. The new generation of civil and structural engineers are encouraged to look into these innovation, philosophy and technologies to enhance the overall efficiency and sustainability of building design and construction.

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