



Title: Engineering of Guangzhou International Finance Centre

Authors: Michael Kwok, Director, Arup
Alexis Lee, Arup

Subjects: Building Case Study
Structural Engineering

Keywords: Optimization
Structural Engineering
Structure
Sustainability

Publication Date: 2017

Original Publication: International Journal of High-Rise Buildings Volume 6 Number 1

Paper Type:

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 Unpublished conference paper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 Unpublished

Engineering of Guangzhou International Finance Centre

Michael Kwok[†] and Alexis Lee

Arup, Huaihai Plaza, 1045 Huaihai Road (M), Xuhui District, Shanghai 200031, China

Abstract

The Guangzhou International Finance Centre (IFC) is a landmark building that symbolizes the emerging international strength of Guangzhou, China's third largest city. It is also one of the dual iconic towers along the main axis of Guangzhou Zhujiang New Town. Arup adopted a total engineering approach in embracing sustainability and aiming at high efficiency solutions based on performance-based design principles covering structures, building services, fire engineering, vertical transportation, and façade performance to constitute an efficient and cost-effective overall building design. Through dynamic integration of architectural and engineering principles, Guangzhou IFC represents a pioneering supertall building in China. It adopts a diagrid exoskeleton structural form that is clearly expressed through the building's façade and gives the building its distinctive character. The aerodynamic shape of the building not only presents the aesthetic quality of elegant simplicity, but also reduces the effects of wind, thereby reducing the size and weight of the structure. State-of-the-art advanced engineering methods, such as optimization techniques and nonlinear finite element modelling, were applied in parallel with large-scale experimental programs to achieve an efficient and high-performance design taking into account the constructability and cost-effectiveness for a project of this scale.

Keywords: Super-tall building, Diagrid, Sustainability, Optimisation, Nonlinear analysis

1. Introduction

Being the fourth tallest building in China and the ninth tallest in the world at the time of its completion, the 432 m-tall tower of Guangzhou International Finance Centre (aka. the West Tower of the Guangzhou Twin Towers) was initiated as an international design competition held by the Guangzhou City Planners in 2004.

As the winning partner with Wilkinson Eyre Architects, Arup was responsible for the multi-disciplinary engineering for this landmark building - one of the twin iconic towers along the main axis of Guangzhou Zhujiang New Town.

1.1. Architectural Concept

The 103-storey high rise is characterised by a rounded triangular plan and double-curved elevation in the shape of a spindle set out with the widest point at approximately a third of the building height, tapering to its narrowest point at the top. Included in the mixed-use development were 69 floors of grade-A office space, 34 floors of luxury five-star hotel at top of building with an open central atrium, and a top observation area, which added up to a gross floor area of 450,000 m² in total. It is also the first super-tall building in China that adopted diagrid exoskeleton structural form which is clearly expressed through the



Figure 1. Guangzhou International Finance Centre.

[†]Corresponding author: Michael Kwok
Tel: +86-21-3118-8888; Fax: +86-21-3118-8882
E-mail: michael.kwok@arup.com



Figure 2. The signature diagrid exoskeleton.

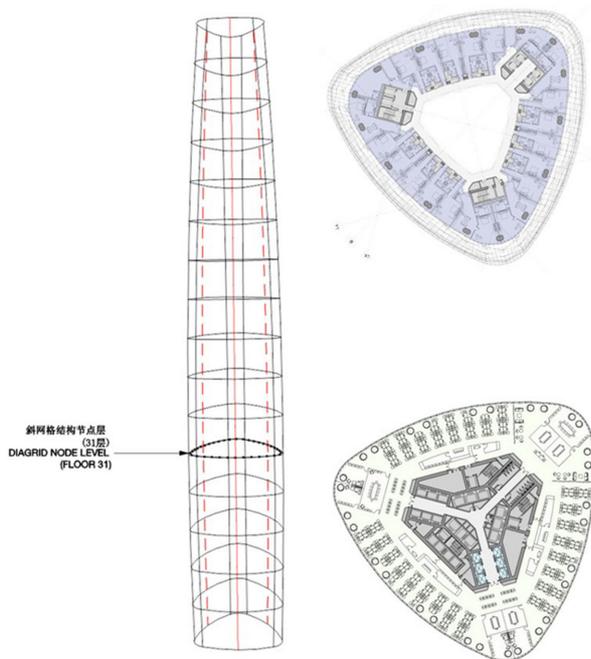


Figure 3. Typical layout plan.

building's façade and gives the building distinctive character.

1.2. Sustainable Solutions

Arup's multi-disciplinary teams, including structure, façade, traffic, building services, vertical transportation, building physics, fire and wind engineering located in Hong Kong, London and Shenzhen, together developed a truly integrated design by adopting the holistic approach. The building has been designed to be low carbon and sustainable. In addition to those fundamental passive measures such as orientation, sustainable building systems have been incorporated into the design which address issues such as comfort, maintenance and cost while paying due

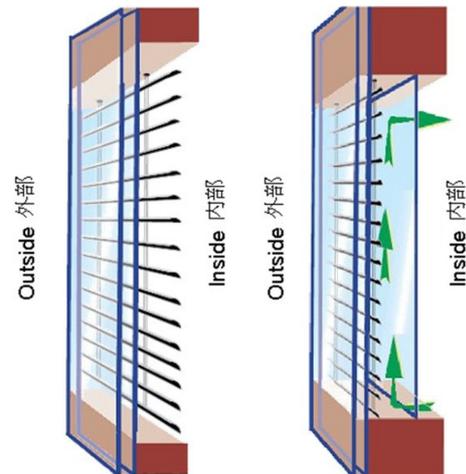


Figure 4. Construction of single skin façade and active airflow curtain wall.

regard to environmental sustainability and energy conservation.

2. Double Skin Ventilated Façade System

The architectural aspiration of Guangzhou IFC is for a building, which is sleek in nature, curvaceous and transparent allowing the structure of the building to be revealed. The cladding's ability, or efficiency, to protect the internal spaces from the heat or the cold of the external environment directly affects the design of the environmental systems for the building. The design and performance of the cladding therefore directly affects the amount of energy that a building must consume in order to heat, cool and light the spaces within.

2.1. Façade Options

At the time of design, all the public buildings designed in China should comply with the requirements stipulated in the Chinese Code GB50189-2005 "Design Standard for Energy Efficiency of Public Buildings". This provides guidance for building design with an adequate level of thermal and energy performance to ensure efficient use of energy. The façade glazing is designed to achieve a maximum shading coefficient of 0.35 based on a window to façade ratio ≤ 0.7 - This should be considered high performance solar glazing.

Three façade design options were studied including single skin façade with double glazed units, an active airflow curtain wall with venetian blinds and active airflow curtain wall without venetian blinds.

2.2. Thermal Performance Analysis of Façade Design

The Tower has a triangular shape with three main façade orientations facing North, North West (NNW), East South East (ESE) and South West (SW). The orientations are

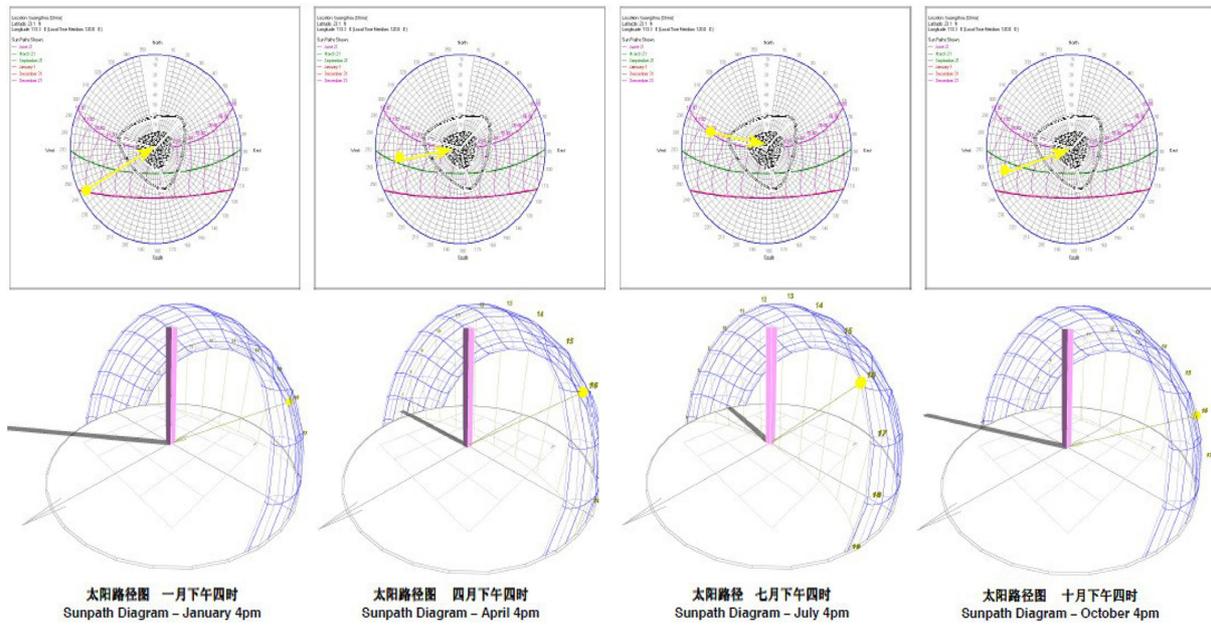


Figure 5. Solar pattern during different seasons.

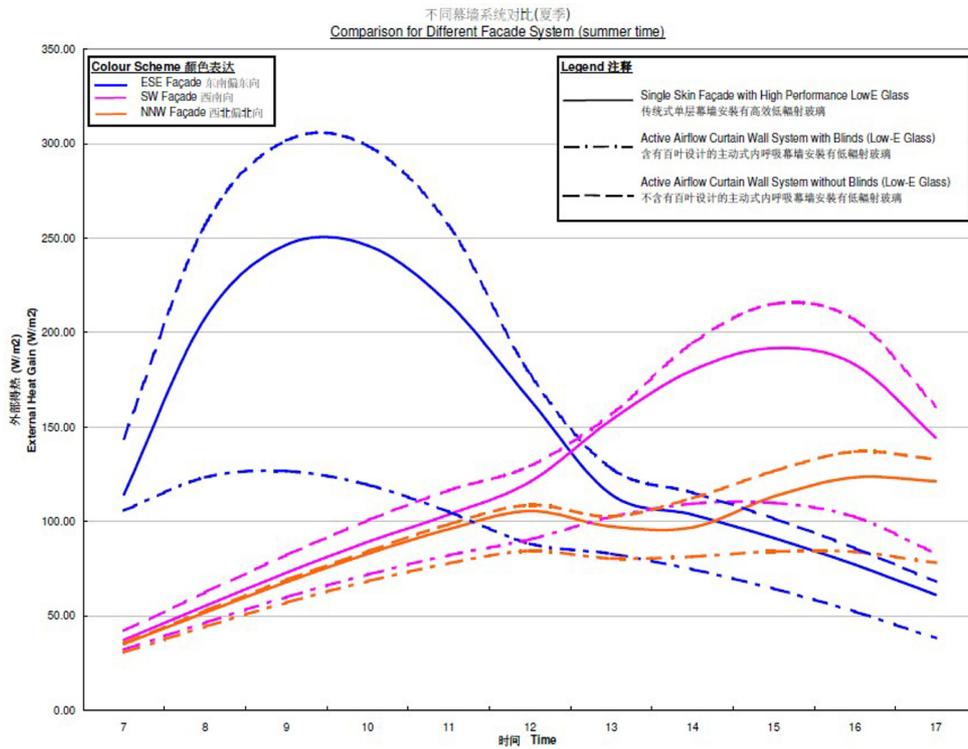


Figure 6. External heat gain through different façade system.

established by considering optimisation of views, solar insolation and daylight performance.

Based on the relationship between the solar geometry in summer during occupancy period and building orienta-

tions, the minimum solar altitude required to completely cut-out the majority of direct solar radiation on ESE façade is about 55° to horizontal, whereas for SW façade is about 20°. NNW façade receives primarily diffuse solar

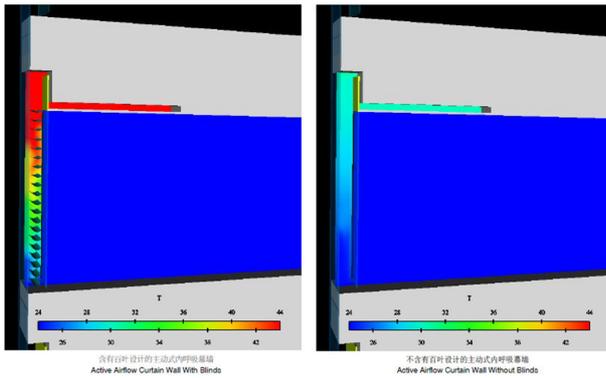


Figure 7. Air temperature distribution at air cavity.

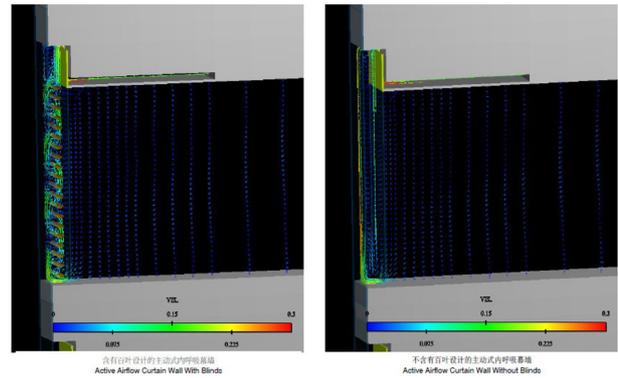


Figure 8. Air velocity distribution at air cavity.

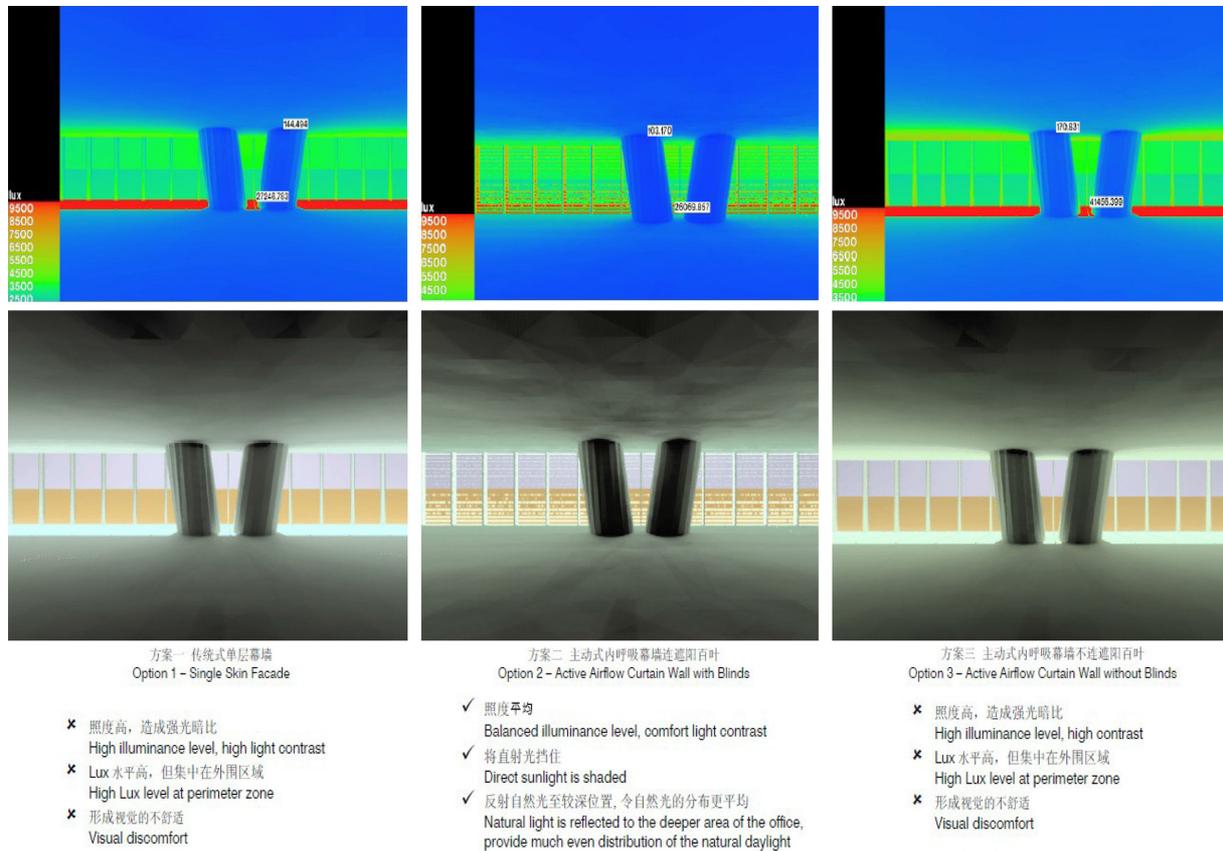


Figure 9. Daylight performance of different façade options.

radiation throughout the year. Therefore the effectiveness of using external shading is limited.

The thermal performance of a façade system is affected by many parameters, which include solar transmittance, shading coefficient and shading devices etc.

For all the three façade options, the external heat gain on the different façade orientations varies with time due to the variation in the sun’s position. The external heat gain on the ESE will be highest in the morning time around 9

a.m., while those on SW will be highest in the late afternoon. An active airflow curtain wall with blinds was identified to perform the best in terms of energy reduction on these façades. The figure below shows the effectiveness of the solar protection systems throughout the day, it can be seen that the active airflow module with blinds works most effectively.

An airflow curtain wall uses the exhaust indoor air to remove the external heat trapped in the cavity of the cur-

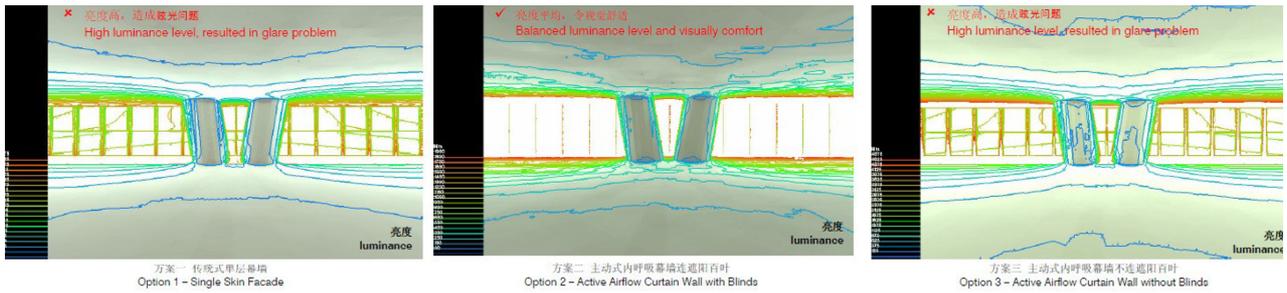


Figure 10. Luminance Level of Different façade System.

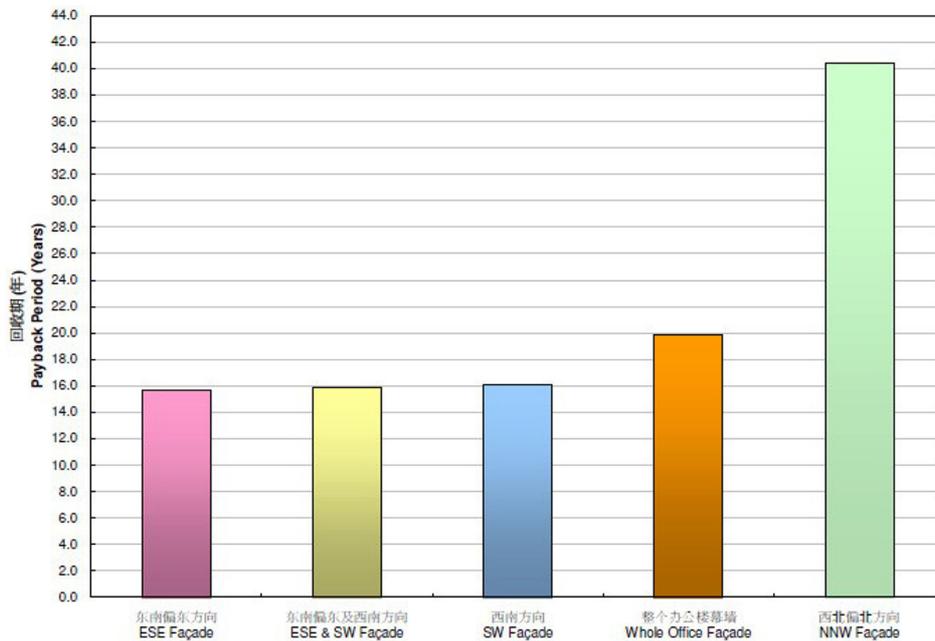


Figure 11. Payback period of active airflow curtain wall.

tain wall. Its energy-saving performance is determined by the amount of heat trapped in the cavity.

Blinds act as solar shading device that block and absorb the direct solar heat gain which increases the temperature in the cavity. The exhaust air from the bottom of the window will flow across the horizontal blinds, taking the heat from the blinds to the outside. Without blinds, the exhausted airflow can only remove limited heat from the glass surface as they would only pass along the outer pane of the façade. The figures below show the difference in cavity temperature and air movement when blinds are used or not used, It can be seen that blinds are effective at blocking and trapping heat before it reaches the occupied space.

2.3. Daylight Performance of Façade

The visual comfort due to the daylight effect has a direct impact on the ability for occupants to perform their tasks effectively. The single skin façade and the active airflow

curtain wall without blinds have a higher lux level at perimeter zone near the window due to direct sunlight. The active airflow curtain wall with blinds provides more evenly distributed natural daylight by shading direct sunlight and reflecting light to the deeper areas of the office. The figures below show the daylight simulation results.

2.4. Glare Analysis

A glare problem may exist when occupants have to work while facing a very bright window or light source. Glare can have two effects. First, it can impair vision, in which case it is called disability glare. And the other effect is discomfort, in which case it is called discomfort glare. The single skin façade and the active airflow curtain wall without blinds has a stronger light contrast, as compared to the active airflow curtain wall with blinds option, the contrast creates discomfort glare. The active airflow curtain wall with blinds has the optimum

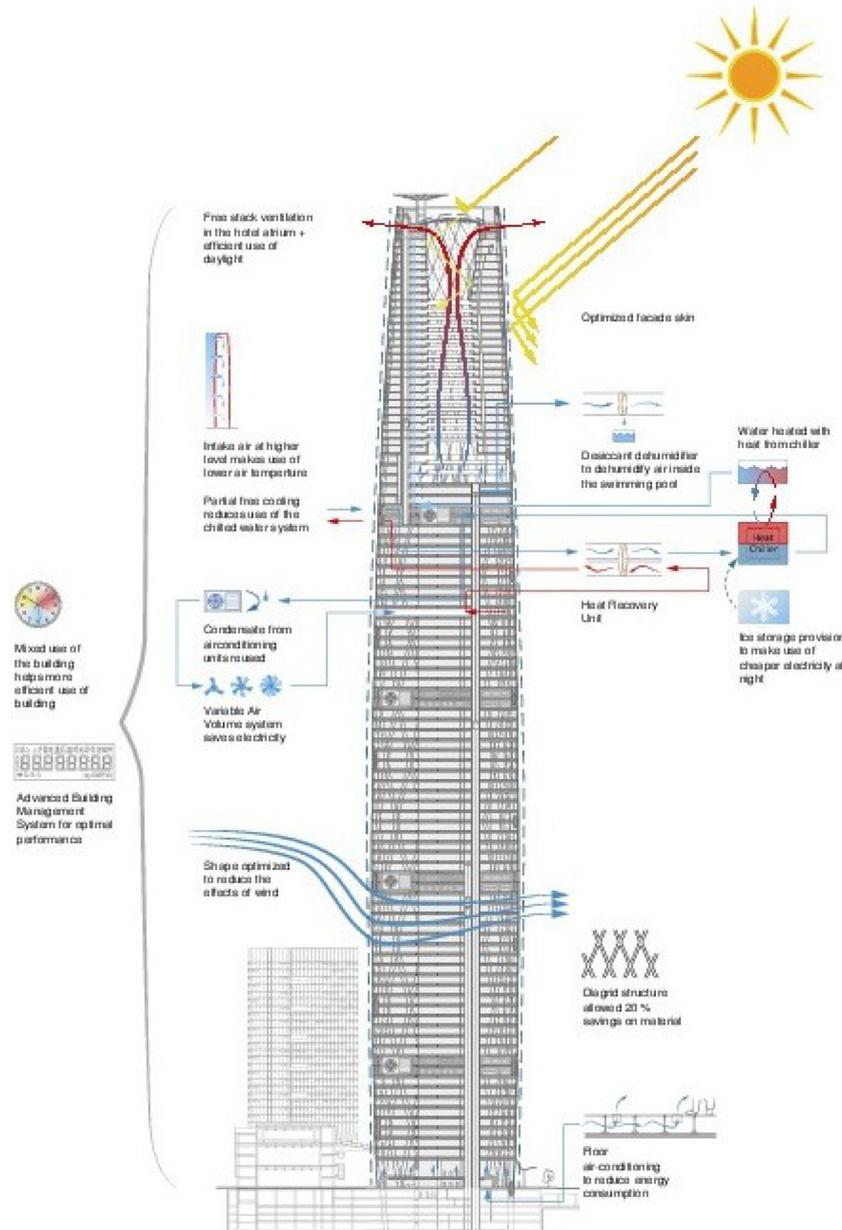


Figure 12. Building sustainability model.

performance.

2.5. Cost Analysis

Additional costs are required for installing active airflow curtain wall system. The main cost difference is due to the different requirements on the aluminium sections, the HVAC connections and the associated installation costs. The system paybacks range from 16 to 41 years depending on the extent.

The active airflow curtain wall with blinds has numerous benefits relating to energy savings, more evenly distributed daylight, glare mitigation and thermal comfort. Despite its environmental benefits, the prohibitive cost and

added maintenance of the active airflow curtain wall system means that the system could not be implemented for the West Tower. Instead, the single skin façade with an added layer of blinds was adopted in the final design.

3. Energy-efficient Building Services

Usually, in low-rise building, a single usage of building is very common. The plant room planning and its spacing requirement is simpler than a composite one as composite building implies more systems within a building. For super-high rise building, due to the large floor area and also the number of floors in a building, the building can divide

into several zones for different functions and so it usually serves as the composite building.

Regarding to the composite building, MEP systems will be divided according to the different zones and property management in order to suit the various functional areas. In order to segregate the responsibility and operational requirements on each zone of building, the MEP equipment shall repeat to allocate among these different architectural zones which results in more space reserved for composite building than single usage building. In overall, composite building may consume more total plant room areas.

As it is believed that single purpose high-rise building is normally less attractive from developer's view than a building which has diversified functions. In consideration of the architectural zoning, a balanced consideration between determining the number of functional areas and plant room areas shall be taken into account when designing a tall building.

For Guangzhou IFC, the building is divided into different main sections - office, retails and hotel. With several architectural zonings, the MEP zoning for LV distribution is also divided into different portions for each section of building, in turn the total number of plant rooms for accommodating equipment may increase due to the increased number of MEP distribution zones. Electricity is obtained from Zhujiang new district substation via 5 groups of dual 10 kV feeders. These feeders are connected to 4 power supply system zones. Diesel generator is installed as emergency backup.

High-rise buildings require increased structural integrity and additional risers for the chilled water, cold water and sprinkler systems etc. Closely coordinated with the structural design and adapt to vertical configuration to optimize system working pressures is required for MEP systems. For example, in consideration of the water side system pressure break, the entire building is divided into different pressure zones separated by heat exchangers installed at mechanical floors in order to avoid equipment and pipework withstanding high pressure and to control the building investment cost.

3.1. Centralised/decentralised System

In addition to the zoning for composite building, the use of centralized and de-centralized systems is considered. The building is with super high and huge of gross floor areas, de-centralized MEP systems is adopted subject to specific design requirements and constraints, such as air-conditioning system, power supply system and lift system. Centralized system is applied for fire services system and rain water system.

Both de-centralized and centralized systems have its advantages. After considering the characteristics of both centralized and decentralized AHU system and overall architectural planning, centralized primary air handling units (PAU) with de-centralized air handling units (AHU) are adopted in West Tower. Centralized PAU can put the

air louver together to dedicated floors, which are mechanical floor, podium and roof at West Tower. 2 numbers of de-centralized AHU plant room are located on each typical floor to accommodate the AHU.

3.2. Holistic Heating/cooling Option

The air-conditioning system in office is using Variable Air Volume (VAV); it is not only an energy efficient system, but also minimises maintenance work and installation of chilled water pipework in the office space compared to a fan coil system. As it is an all air system, it can introduce more fresh air into the office space during transient periods to minimize chilled water demand and enhance indoor air quality. Air-conditioning condensation from air handling units is collected and then reused for irrigation.

The integrated energy systems were optimised through computational simulation of cooling load and energy analysis based on 8,760 hours of Typical Meteorological Year data. The results were used to recommend system selection, optimise HVAC and review system reliability. Cooling analysis was performed to assess the influence of stratification in the hotel portion and to determine the most efficient air-conditioning systems for the large atrium space. This led to the adoption of an under-floor air-distribution system, which was 15% more energy efficient in comparison to a ceiling supply system, in the hotel entrance lobby.

Such a holistic consideration on energy consumption also allowed us to tailor the system design to suit the needs of the sub-tropical climate of Guangzhou. During winter and autumn periods, the building makes use of free cooling whereby plant rooms towards the top of the building draw in cooler and drier air from outside and this is in turn used for space conditioning of the office component. This minimizes the operation of the chilled water system. Conversely, during the hot and humid summer months, residual cooling energy from the office exhaust is captured in an air-to-air heat recovery device to pre-cool the incoming fresh-air. To enable these strategies, a special study was carried out to assess the air flow characteristics at the higher level mechanical floors under various wind conditions.

3.3. Air-side Heat Recovery

Total enthalpy wheel is provided for the fresh air heat recovery serving hotel gymnasium and restaurant where a large amount of fresh air is required. Reduced ventilation load is one of the key energy saving strategies, which will benefit to decrease the building cooling load demand, as well as to enhance air-side heat recovery performance. Air-side heat recovery recover cooling/heating energy from exhaust air to reduce the cooling/heating fresh air load. Desiccant dehumidification is provided for fresh air treatment serving hotel swimming pool such that latent load can be reduced.

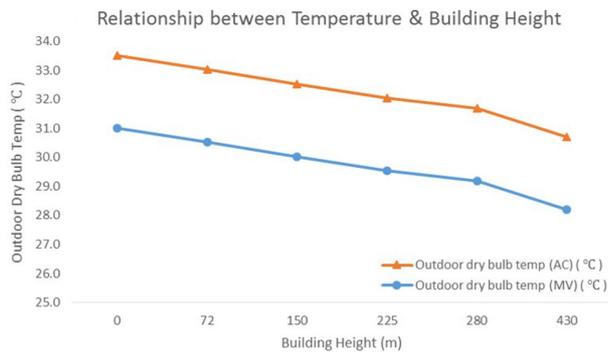


Figure 13. Dry bulb temperature variation with height.

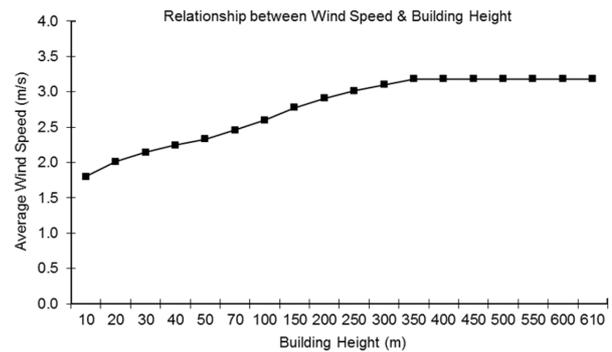


Figure 14. Wind speed variation with height.

3.4. Demand Control Ventilation

CO₂ sensors are installed at West Tower to implement demand control ventilation to reduce unnecessary over-ventilation that might result if air intakes are set to provide ventilation for a maximum assumed occupancy. This CO₂ based demand controlled ventilation is used to modulate outside air ventilation based on real occupancy.

3.5. Under Floor Air Distribution (UFAD)

Under Floor Air Distribution makes use of the floor plenum to distribute the conditioned air supply at low pressure, and generally creates better mixing as the air is supplied at floor level and returned at ceiling level. The system can provide a better indoor air quality and thermal comfort compared with the traditional ceiling supply. UFAD could also benefit from the system energy saving due to higher supply air temperature (16-18°C) and lower fan power (benefit from utilizing the air buoyancy).

3.6. Heat Recovery Chiller

Heat recovery chiller make use of the waste heat energy generated from chiller to heat up a water loop instead of disperse the heat through heat rejection system. With heat recovery chiller at Guangzhou IFC, the waste heat is used to preheat water for the hotel and can reduce the chance of environmental pollution.

3.7. Outdoor Temperature at High Level

Outdoor dry bulb temperature has significant decreases at higher building level, see below figure. With this advantage, less energy will be used to treat the outdoor air to desirable air temperature and serve at occupied zones.

3.8. Degrading Exhaust Discharge Performance at High Level with Elevated Wind Pressure

Exhaust air discharged at high level of the building creates a potential problem affecting the ventilation system performance. Since high wind speed always occurs at a height over 200 m, the wind-facing side façade would maintain positive pressure. The positive pressure would create a force to obstruct air flow from the building if

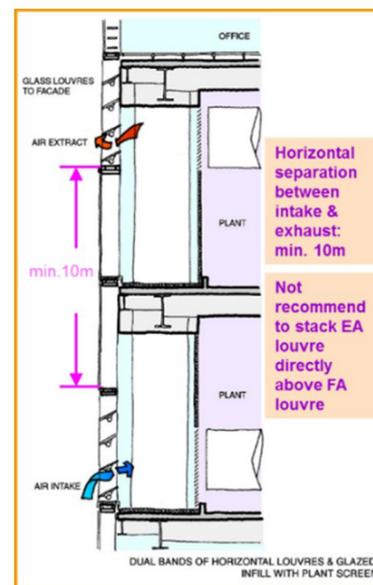


Figure 15. Separation of air intake and exhaust at height.

exhaust louver is located at that position. The adverse impact under the worst situation was investigated in Guangzhou IFC and hence fine tune the design of exhaust air louver to overcome this problem. The measure is to discharge air at negative pressure zone, at the same time, exhaust air louver shall not directly stack above the fresh air louver, at least 10 m separation is required, see the figure below.

3.9. 24-hour Chilled Water Supply System

Electricity supply from emergency generator is provided to a number of chillers to allow 24-hour essential chilled water supply. 24-hour essential chilled water pipes is provided for future tenant's connection. Both high zone and low zone are provided with 2 separate pairs of 24-hour essential chilled water supply & return, which are interconnected to each other (normally close) in mechanical floors. This allows continuous 24-hour essential chilled

water supply to every point even if water pipes failure is found.

3.10. Fire Services System

The fire services water storage tank is built at the roof for all fire services systems of the building. In case of fire and any pump malfunction, water already stored at the roof tank can still be supplied by gravity for fire hydrant and sprinkler systems for fire suppression in order to enhance the system reliability.

4. Traffic Planning

The traffic engineering facilities and arrangement were designed principally based on the national standards with adjustments to local city guidelines.

4.1. Arrangement of Driveway and Ramps

In order to cope with the architectural design and arrangement, there were 7 m right-in and right-out access roads on the east side of the tower to provide drop-off and pick-up services for the office tower, shopping malls and apartments. On the near side of the driveway, there was an exclusive drop-off and pick-up lane to serve the purpose and hence minimise the impact on the access road. 50 m away from the junction of Zhujian Main Street West and South Hua Cheng Road on the south section of Zhujian Main Street West, there was a two way service road of 7 m wide leading to the south of the tower providing service for hotel, multi-purpose hall and office car park ramp. This arrangement was to let internal traffic activities to be done within the development area without affecting the public traffic outside the tower area. However, the junction formed by this access road having about 50 m away from the junction of Zhujian Main Street West and South Hua Cheng Road might not meet the Standard requirement, but in consideration of the South Section of Zhujian Main Street West functioning as an auxiliary road, the junction spacing of 50 m would be acceptable.

4.2. Parking Facilities

On ground level, there was a limited number of parking spaces provided for management purpose and short staying visitors. There were drop-off bays provided on the north and east side of the tower for shopping centre and office tower respectively. On the west side of the development, there were two drop-off and pick-up facilities for serviced apartment, hotel and multi-purpose hall. The main car park facility was located at basement 2, 3 and 4 providing 1,500 parking spaces which satisfy the demand and requirements. There were also 20 loading and unloading bays for goods delivery purpose.

4.3. Traffic Flow

The traffic flow volume generated and attracted by the development of Guangzhou IFC was assessed. All junc-

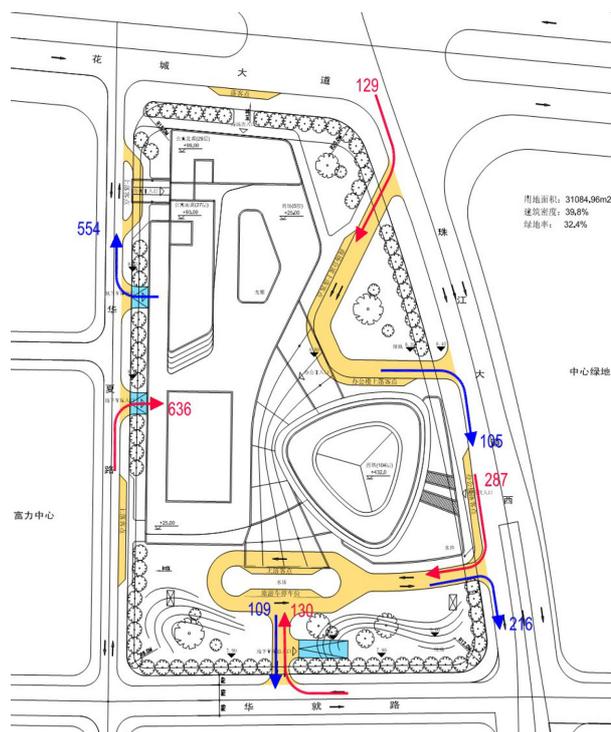


Figure 16. Traffic flow assessment.

tions formed by the development access and ramps with external road network were controlled by priority junction control method and safe the installation of traffic signals. The volume-to-capacity ratio of the service road in the southern area of the development was about 0.53 which shows this access road could provide good service condition for development traffic. On the planned road just west of the Tower, the volume-to-capacity ratio was 0.6 which also showed that this road could provide the level of service in the good category.

5. Fire Safety Strategy

Fire safety is one of the critical issues on the design of super-tall buildings. A series of unique features of super-high-rise buildings such as high occupant load in long and vertical evacuation, high risk in fire spread along external walls, etc. bring great challenges to engineers. Therefore, it is important to enhance the fire safety of super-tall buildings by feasible strategies during the design stage.

The fire safety design of Guangzhou IFC is generally in accordance with the prescriptive requirements from China fire safety code. Tailored-made fire safety strategy was proposed on the basis of the unique building features on the aspects of evacuation and smoke extraction. Fire engineering approach was adopted to evaluate the effect of the fire safety enhancement.

Guangzhou IFC is a 103-storey super-high-rise building with 432 m in height. The tower consists of Super-A Class

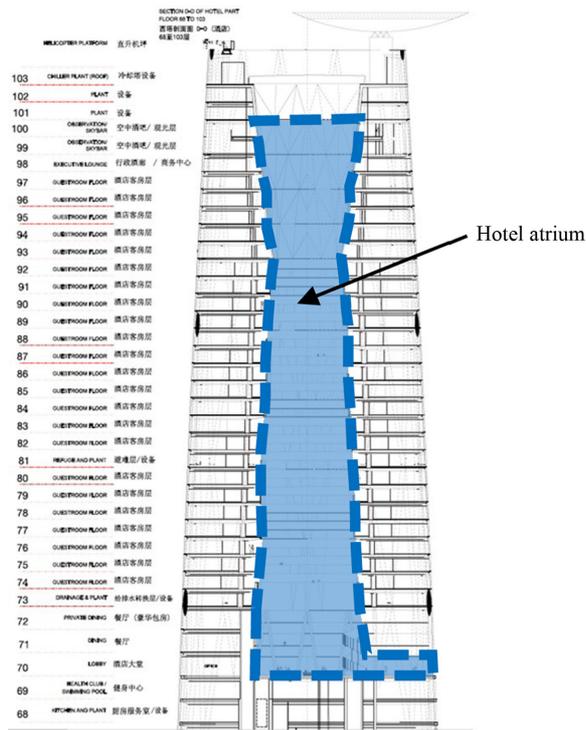


Figure 17. Hotel atrium from 70/F to 100/F.

office floors (1F-66F) and 5-Star hotel floors (69F-103F). There is a grand atrium in the hotel and connected from L70 to L100, which is shown in the following figure.

5.1. Evacuation Design

The evacuation time in super-tall buildings is usually very long because large number of occupants have to travel inside the staircases for long vertical distance. Therefore, safe evacuation was the key issue in fire safety design of this project.

The total width of staircases in Guangzhou IFC was designed on the basis of occupant load to fulfill the China fire safety code requirement, i.e., 1 m/100 person. The total egress width of protected staircases in each floor is sufficient for all occupants' evacuation simultaneously. Three evacuation staircases are provided for the typical office floors and two are provided for the typical hotel floors, which are shown in Figs. 18 and 19, respectively. The occupants on the observation deck or the sky bar at the top of the building are designed to discharge into the two staircases in hotel zone for evacuation.

The egress width (i.e., staircase number & width) was optimized according to occupant load in different function zones (i.e., office/hotel floors between two refuge floors) instead of being consistent through the whole tower. For high density floors, e.g., restaurant, banquet area, etc., protected staircases are provided to increase the egress width locally and discharge to refuge floor immediately below this function zone as is shown in Fig. 20.

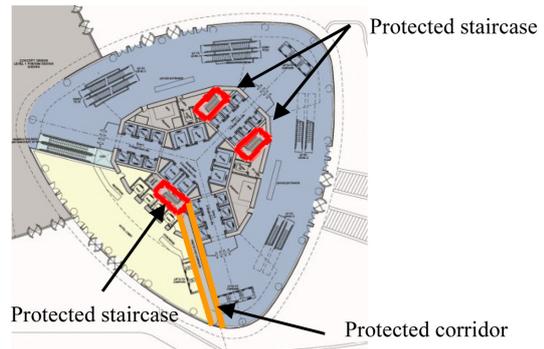


Figure 18. Arrangement of three protected staircases on typical office floors.

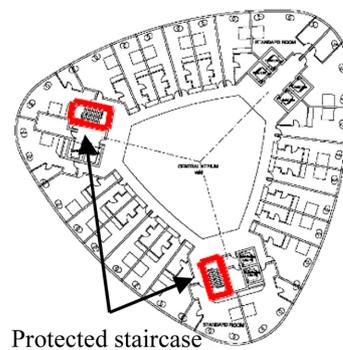


Figure 19. Arrangement of two protected staircases on typical hotel floors.

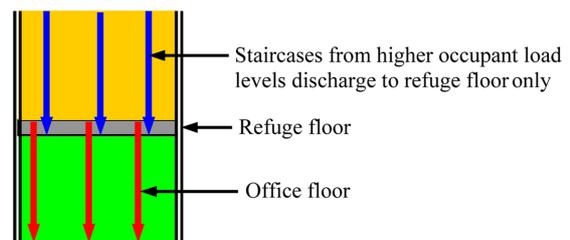


Figure 20. Egress width optimized according to occupant load in different function zones.

5.2. Travel Distance

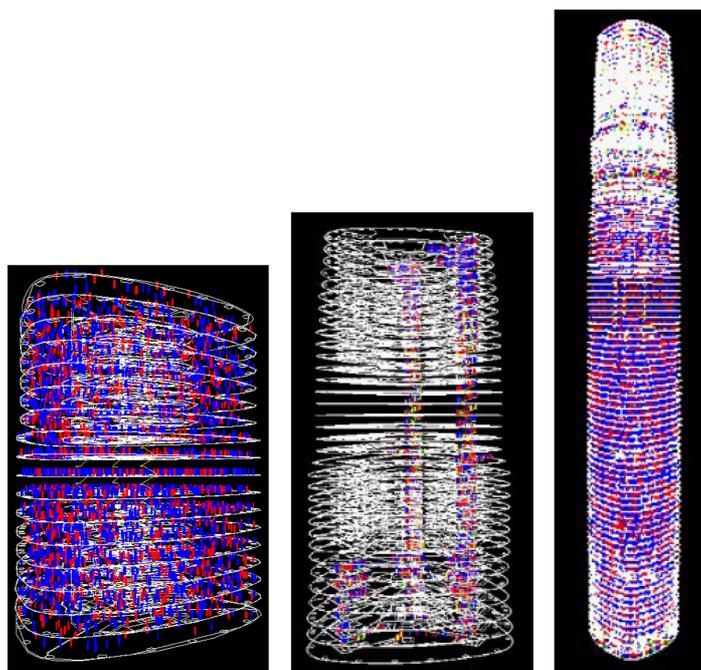
At least two exits (i.e., protected staircases) are provided for occupant evacuation in each compartment of typical floors. For office floors, the travel distance for occupants to reach the nearest protected staircase is within 30 m. For hotel floors, the maximum travel distance inside some Executive Suite rooms exceeds 15 m (within 30 m) due to luxury room area. Active fire protection systems, e.g., sprinklers installed in the hotel corridors and the tailor-made smoke control system in hotel atrium are des-

Table 1. Capacity of assembly area in refuge floors

| Refuge Floor | Served Floors | Refuge Area (m ²) | Refuge Capacity (person) | Occupant Load (person) |
|--------------|---------------|-------------------------------|--------------------------|------------------------|
| F1 | 1-12/F | Outside of Building | N/A | 2,549 |
| F13 | 13-30/F | 1,056 | 5,280 | 4,710 |
| F31 | 31-48 | 1,042 | 5,210 | 4,738 |
| F49 | 49-66/F | 938 | 4,690 | 4,508 |
| F67 | 67-80/F | 426 | 2,310 | 2,092 |
| F81 | 81-102/F | 342 | 1,710 | 1,668 |

Table 2. Evacuation time of refuge floors.

| Refuge Floor | Served Floors | Evacuation Time |
|--------------|---------------|-----------------|
| F1 | F1-F12 | 11 min 34 sec |
| F13 | F13-F30 | 23 min 08 sec |
| F31 | F31-F48 | 23 min 08 sec |
| F49 | F49-66 | 23 min 08 sec |
| F67 | F67-F80 | 10 min 44 sec |
| F81 | F81-F102 | 11 min 25 sec |

**Figure 21.** Fire evacuation simulation.

igned to compensate the non-compliant issue of excessive travel distance, which is verified by computational evacuation and smoke control simulation.

5.3. Refuge Floors

In order to be consistent with the architectural elevation and structural arrangement of the building, refuge floors are provided at every 17 floors in office zones and 19 floors in hotel zones, which somehow deviated from the code requirement of provision of refuge floor in every 15 floors. As is shown in Table 1, the refuge area in refuge

floors were verified to be capable to cater for all occupants in the immediately above function zone. In addition, the helicopter-pad at the top of the building was also considered as supplement for refuge and rescue.

5.4. Computational Evacuation Simulation

For this super-tall building, phased evacuation strategy was proposed under normal fire conditions. The whole tower evacuation (i.e., total evacuation) is necessary if fire spread is out of control or in case of other extreme situations (e.g., terrorist attack). The evacuation time in

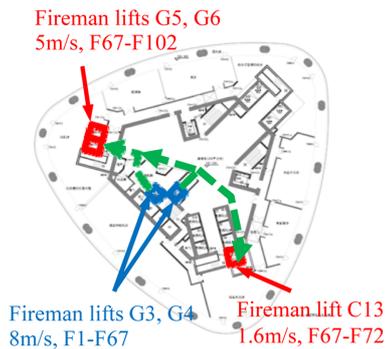


Figure 22. Fire lift transfer at R67.

each function zone as well as the total evacuation scenario was achieved by computational evacuation simulations. The STEPS models for the study of phased evacuation (i.e., evacuation of function zones) and total evacuation are illustrated in the following figures.

The evacuation time of 7 function zones are summarized in Table 2, which is demonstrated that occupants can be evacuated into the refuge floor immediately under the fire floors generally within 24 min.

5.5. Fireman Lifts

The fireman lifts in Guangzhou IFC are designed to have a transfer at R67 (i.e., Refuge Floor L67) between office and hotel floors due to the restraint of building layout. Dedicated protected corridor are provided as the transfer route in R67. It is estimated that fire fighters can reach the top floor in approximate 111 s including the aforementioned transfer.

5.6. Smoke Control

Natural smoke extraction system by 2% openable window of the floor area at the façade was designed in typical office floor. Computational Fluid Dynamics (CFD) models are adopted to verify the available safety egress time due to smoke spread. The CFD model and simulation results are illustrated in the following figures.

The hotel atrium is 30-storey high and connected from L70 to L100. Fire shutters are employed to separate the restaurant floors from atrium in L71 and L72. The hotel rooms located from L73 to L97 are separated from atrium by fire-rated walls and fire-rated doors. Fire-rated glass is designed to enclose the atrium from L98 to L100 and isolate the circulation area. Mechanical smoke extraction system is provided in this large atrium. Two dynamic smoke extraction points are designed in L81 and the other two at the top of the atrium. Fire engineering approach is employed to verify the smoke control strategy. Numerical study on dynamic smoke extraction is illustrated in the preceding figures.

The comparison of available safe egress time (ASET) from CFD models and the required safe egress time

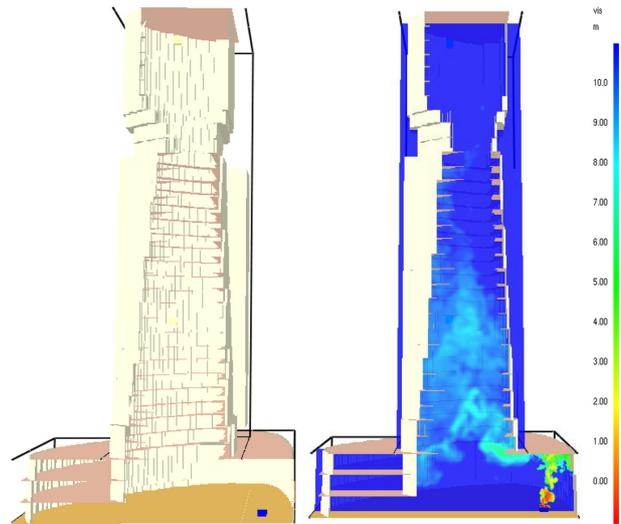


Figure 23. CFD modelling of smoke filling condition in hotel atrium.

Table 3. Safe egress time of refuge floors

| Fire Scenario | Floor | ASET (s) | RSET (s) |
|---------------|----------|----------|----------|
| Office floor | 4-66/F | 260 | 195 |
| | 70/F | >750 | 475 |
| | 73-92/F | 390 | 325 |
| Hotel atrium | 93-97/F | >750 | 395 |
| | 98-100/F | >750 | 480 |

(RSET) in fire scenarios of office floor and hotel atrium is shown in Table 3. It is shown that fire safety can be achieved due to ASET larger than RSET.

6. Vertical Transport

Staircase, lift, toilet and structure are the dominant components for the determination of building core size. In a high-rise building, due to large GFA of the building, Mechanical, Electrical and Plumbing (MEP) services become one of the dominant components and major factors for the determination of core size. With less MEP services occupying the core area, more rentable area per floor will be achieved. Hence, a comprehensive design consideration on the core size in a high-rise building becomes one of the significant missions for MEP engineers.

6.1. Floor Efficiency

For various MEP services inside a high-rise building, vertical transportation system is undeniably one of the main design elements comprising the core area as lifts occupy space for lift shafts vertically along the building for passenger transportation. In general, a conventional lift strategy is applied in low-rise building, in which it requires each lift having its own lift shaft. However in high-

rise building, due to giant height of the building, more number of lifts are definitely required to accommodate the increased number of occupants if conventional lift strategy is to be adopted. This implies that more lift shafts and larger core area are required in order to accommodate the increased lift cars. In view of the technical requirements, some innovative lift design strategies – Use of high speed lift, sky lobby concept, use of double deck lifts, are subsequently adopted in Guangzhou IFC instead of conventional lift strategy, so as to optimize the core efficiency.

6.2. Use of High Speed Lift

Application of high speed lift is common in tall building since it can improve the average passenger waiting time and handling capacity. It implies that less time is required for passengers to travel throughout the building than a low speed lift. As a result, lesser number of lifts are required for a tall building which in turn to minimize the total number of lift shafts and to increase the core efficiency.

6.3. Sky Lobby Concept

The sky lobby concept may save up to 50% the lift shafts/areas which can be used for other purposes when compared with the conventional lift strategy. In West Tower, the building is separated into different main lift zones. Office floors in each main lift zones will be further divided into local lift zones. Shuttle passenger lifts will be used to connect the sky lobbies with the main entrance of the hotel area. Passengers have to transfer at the sky lobbies to travel to their destination floors. The most beneficial characteristic of this concept is that lift shafts of lower local lift zones can be sharply used for higher local lift zones and thus it will greatly reduce the total number of lift shafts required for local lift zones. In the conventional approach where sky lobbies are not provided, all lifts would have to depart from the terminal floor to serve different levels. In this case there would be double the lift shafts at typical core when compared with sky lobby concept and it would be impractical for tall building. With sky lobbies, the lifts at different zones can stagger up at the same lift shaft and reduce the overall lift shaft area at the core.

Consideration of the suitable floor location of sky lobby is important in the application of sky lobby concept. In general, the sky-lobby is better to be located at upper floor of MEP and refuge floor so that the lift pit of high zone lifts and lift machine room (LMR) of low zone lifts can be satisfactory allocated. Without putting the sky-lobby on top of the above location, overlapping of the high zone lift pit and low zone LMR will be the adverse consequence which cannot fully utilize the lift shaft.

6.4. Use of Double Deck Shuttle Lift

Double deck shuttle lift, which consists of two lift cars in a single lift shaft, is used in Guangzhou IFC. All shut-

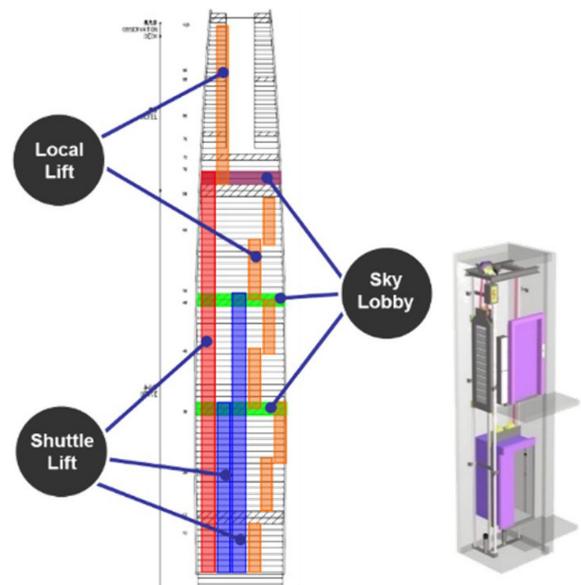


Figure 24. Sky lobby and double-deck shuttle lift.

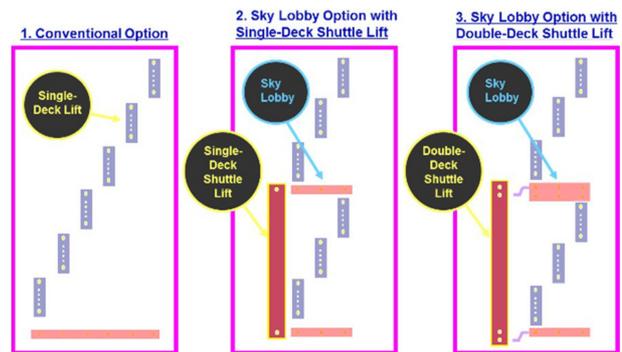


Figure 25. Options of lift efficiency strategy.

tle passenger lifts will serve as passenger lifts for transfer of passengers and luggage to hotel lobby. The cars are vertically aligned and operated together, which provide almost double the capacity of a single deck lift. The application of the double deck shuttle passenger lifts and sky lobby concept is able to achieve up to 50% saving of the shuttle lift shafts/area for other purposes, as compared with the use of single deck shuttle lifts.

In Guangzhou IFC, the office is divided into seven local lift zones: 3 low zones, 2 middle zones and 2 high zones. Sky lobbies are provided for the four upper lift zones and thus two groups of double deck shuttle lifts will transport the passengers from levels 1 and 2 to their sky lobbies (level 30 to 31 and level 48 to 49). The main entrances of low-rise local lift zones are located at level BIM and level 1. Each local lift zone will serve one or more interchange floor to allow local-zone traffic. With this lift strategy, the core efficiency of the West Tower in office floors

Table 4. Summary of lift options

| | Option 1 | Option 2 | Option 3 |
|-------------------------------------|----------|----------|----------|
| No. of Lifts | 36 | 42 | 40 |
| Min. No. of Escalators | 0 | 0 | 4 |
| No. of Lift Shafts | 36 | 24 | 22 |
| Lift Shaft Volume (m ³) | 40,000 | 28,000 | 26,500 |

is around 71%.

Studies among different lift strategies have been carried out at West Tower, Option 1: Conventional option, Option 2: Sky lobby with single-deck shuttle lift and Option 3: Sky lobby option with double-deck shuttle lift. With the use of sky lobby and double-deck shuttle lift, total lift shaft volume is reduced from 40,000 m³ to 26,500 m³.

6.5. Equipment Delivery

Equipment delivery is one of the main concerns for tall building design. Due to the giant height of building, it is quite impractical to assume all main MEP services are fed from the ground/underground level. Imagine if all main MEP systems are climbed up from the bottom of building, the anti-force of systems will be enlarged steadily along with the building height. With this high tension of resistance particularly for tall building, the size for the “connection” of systems will inevitably be increased which includes the cable size in electrical system, duct/pipe size in mechanical systems etc. As a result, distributing the main MEP services into different portions inside the building is practically feasible to overcome the unnecessary increase in the size of “connection”. It can be achieved by distributing plant rooms on ground/underground level and high levels.

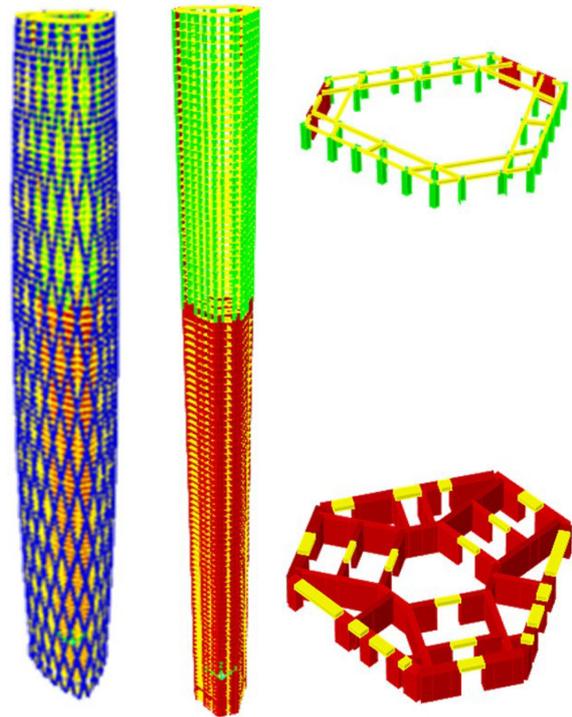
Nevertheless, such design approach faced challenges on equipment delivery as plant rooms were allocated on high levels (which is usually situated over 100 m). As some plant rooms, like transformer room, generator room, chiller plant room and water tank room, the size of equipments are particularly large and cannot be easily delivered by using trolley or by hand. Ultimately, generous equipment delivery route was reserved during the design planning. Several possible measures were investigated to cope with large equipment delivery such as using large services lift and utilizing lift shaft.

- Using large services lift

Services lift of large capacity, usually greater than 3000 kg, is used for the delivery of large equipment up and down the building.

- Utilizing lift shaft

Another measure adopted was to utilize the space along the lift shaft for equipment delivery. In consideration of utilizing the lift shaft, several items, like design provision, maintenance arrangement shall be taken into account. For example, enough space shall be provided for delivery route; the physical dimension of the equipment shall be smaller than the lift car size; the width of the lift door shall be

**Figure 26.** Diagrid and core wall dual system.

large enough to deliver the equipment in and out. Moreover, future maintenance responsibility between lift provider and building management team shall be clearly defined at the outset. The lift provider may also need to disconnect its lift equipment during equipment delivery and maintenance in accordance with the contractual requirements.

7. Diagrid Structural System

A distinctive feature of Guangzhou IFC is the diagrid structural form at the perimeter of the building, which has vastly reduced the amount of structural steel needed in the structure. The building utilised the world’s tallest constructed diagrid structure at the time of construction, which was clearly expressed though the façade and gave the building considerable character. The diagrid exoskeleton perimeter structure was formed by inclined structural members of concrete filled steel tubes, which provided both direct gravity load path for the building weight and high lateral rigidity against wind effects and earthquake actions. The tubular diagrid structure noded out every 12 stories to form 54m-high giant steel diamond pattern.

The 432 m height of the tower exceeded the height limit in Chinese code of 230 m. There were 103 floors above ground and four basement floors below ground. The building utilized a tube in tube system with perimeter diagrid structure and a central reinforced concrete core at the office levels. At the hotel levels, the core walls were rep-

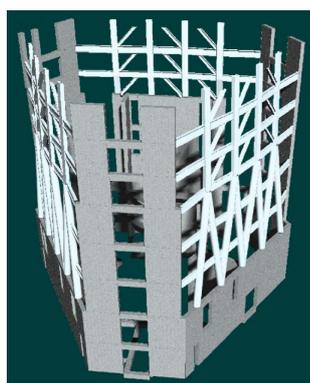


Figure 27. Column transition at hotel lobby floor.

laced by a braced frame tube. The two systems provided both gravity and lateral resistance. The diagrid system behaved as an external tube which is fully braced and members are subjected mainly to axial forces.

The perimeter diagrid structure was set out to follow approximately the double-curved elevation of the tower. A 30 node, 27 m high diagrid module was adopted. Facing of structural form resulted in straight inclined members that change orientation at node levels. The diameter of the diagrid members at building base is 1800 mm with tube wall thickness at 50 mm. The diameter gradually reduces at 50 or 100 mm increments at the node floors. Diagrid members at top of building was sized at 950 mm in diameter with 30 mm tube thickness. The periphery wall of central core was 1.2 m thick in the basement, 1.1 m at ground level and gradually reduced 500 mm below the hotel lobby level. The internal core walls varied from 600 mm to 500 mm thick.

While the perimeter diagrid system provides good later stiffness for tower, it was not the only system that contributes to the overall stability of the building. The central core was designed to endure vertical loads as well as lateral forces. The central core of office floors only extended up to the bottom of the hotel zone, and was then replaced by braced steel frames supported off the core walls below to create an open atrium. The inclined internal braces situated along the separating walls between guestrooms and hotel corridors have compensated for the reduction in stiffness due to the stopping of central core in the hotel zone. This internal steel frame structure also provided the lateral restraint effect to the perimeter diagrid at the node levels, and hence some diagonal braces in the hotel area were needed. Extensive coordination was carried out with the architects to minimize impact on building function and to satisfy aesthetic requirement.

7.1. Elastic Analysis

The choice of analysis software used for the project took into consideration on the characteristics of the structure. ETABS was used in the scheme design and prelimi-

Table 5. Dynamic properties of building

| Mode | 1 | 2 | 3 |
|------------|---------------|---------------|-----------|
| Period (s) | 7.78 | 7.74 | 2.62 |
| | (translation) | (translation) | (torsion) |
| Mode shape | | | |

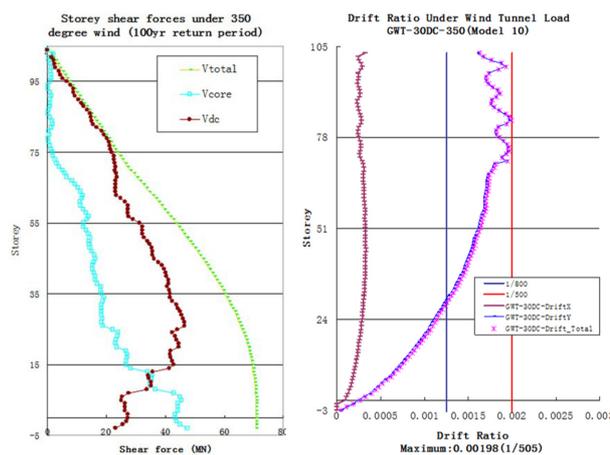


Figure 28. Wind shear distribution and storey drift.

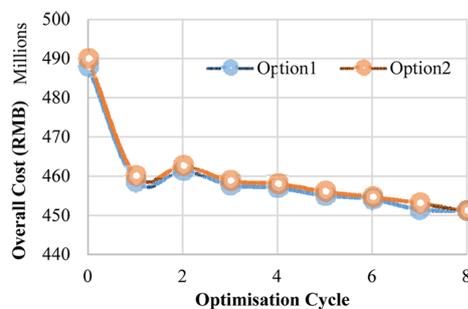


Figure 29. Diagrid optimization history.

nary design stages as the elastic analysis software because of its extensive application for building projects in China and around the world. The ETABS model was created and checked according to the Chinese codes. The analysis results were specifically checked against seismic design requirements of Chinese codes. The Arup in-house software GSA was also used in parallel to allow an independent model for cross checking against the analysis results.

7.2. Optimization Procedure

Extensive computer analysis was conducted to establish the most optimum geometry for the diagonals as well as for the floor layout in relation to the curved nature of the

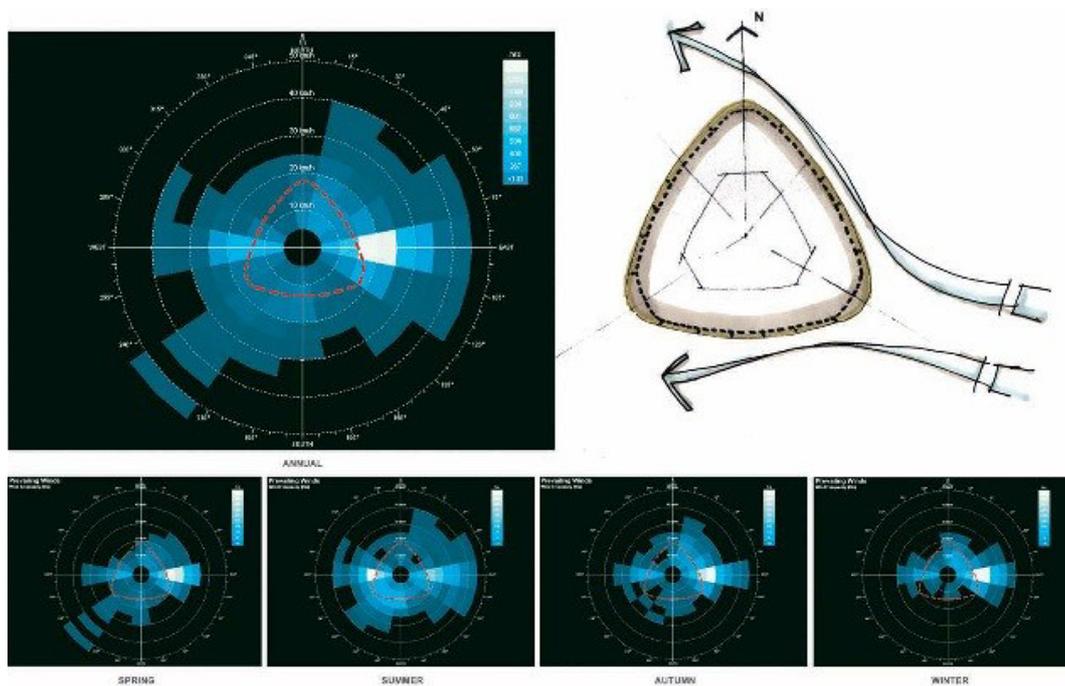


Figure 30. Wind analysis for Guangzhou climate.

building plan and elevation. The original scheme of 36 diagrid columns was trimmed down to the final adopted design of 30 columns. The efficient configuration and optimal sizing of major elements benefited the project in terms of structural cost savings and more flexible use of floor space.

7.3. Wind Engineering

Aerodynamic shaping of the building envelope in the form of curved triangles was developed as an effective means of minimizing the overall wind loading. The corner tapering spreads vortex-shedding over a board range of frequencies and hence benefits the crosswind responses, the rounded building edge alters the flow pattern around the building and reduces the wind excitations.

The wind tunnel test of the main tower was carried out by Shantou University. It was required to determine the following by wind tunnel manometric test, dynamometer check and wind environment test: the average wind pressure distribution and peak wind pressure distribution and attached apartment block, the average wind load, the equivalent static wind load on every floor and foundation, the acceleration response at the top of the building.

In addition to evaluate the residents' comfortability and the passers' height wind environment around the building. In order to consider the possible wind disturbance of future Guangzhou East Tower on Guangzhou IFC, all manometric test, dynamometer check and wind environment test were carried out in two load cases: one was without Guangzhou East Tower, the other with Guangzhou



Figure 31. HFBB wind tunnel test.

East Tower. The structural damp ratio in wind loads calculation was 0.04. In wind tunnel test, the angle interval was 10° . The building characteristics of wind pressure, wind load and wind speed in thirty-six wind direction angles were obtained from the above three tests. The average wind load, the equivalent static wind load of every floor and foundation of west tower, and the peak acceleration at the top were obtained.

To make sure the comfortability of the residents in the high rise building, the building acceleration of wind induced vibration needed to be considered. The building acceleration obtained from wind tunnel tests were used to confirm whether the building satisfies the requirement of building service function or not. According to test results

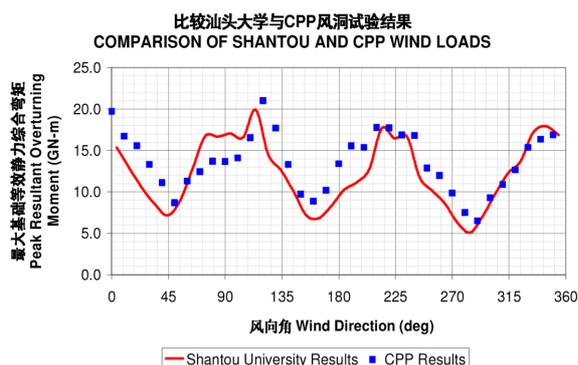


Figure 32. Comparison of tower base overturning moments derived from wind tunnel tests.

provided by Shantou University (the structural damp ratio in acceleration calculation was 0.04), the accelerations at the top of west tower were not more than 20 milli-g under both load cases (load case with and without East Tower), which satisfies the requirement of building service function. Additionally, the USA CPP Company was also commissioned to adopt ARA typhoon to stimulate the ending calculation acceleration. The results also showed that the accelerations at the top of west tower were not more than 20 milli-g under both load cases.

7.4. Seismic Design

The seismic design of the super-tall tower adopted the relevant Chinese national codes, local requirements, the design parameters and response spectrum based on the site-specific seismic hazard assessment carried out by the authorized earthquake bureau.

The actual stiffness of the building structure and hence response to seismic events will be influenced by non-structural elements such as partitions or infill walls. To allow for such effect, reduction factors are applied to the natural period of the structure based on Chinese code recommendation and engineering best practice.

For Guangzhou IFC, most of the core walls were struc-

Table 6. Seismic design categorization

| Categorization Item | Parameter |
|---------------------------------|----------------|
| Building structure safety level | Level 1 |
| Structure importance factor | 1.1 |
| Seismic fortification category | Class B |
| Design reference period | 50 Years |
| Design working life | 100 Years |
| Building height category | Exceed Class B |
| Foundation design category | Class A |
| Foundation safety level | Level 1 |
| Seismic fortification intensity | Intensity 7 |
| Details of seismic design | Intensity 8 |
| Design basic ground acc. | 0.10 g |
| Site category | Type II |
| Characteristic period | 0.35 s |
| Level 1 damping ratio | 0.04 |
| Level 3 damping ratio | 0.05 |
| Seismic design level | Exceed Level 1 |
| Period reduction factor | 0.85 |

tural in nature, and curtain wall was used for the building envelope allowing inter-storey movement. The stiffening effect of non-structural partitions in office zone will be small, hence, 0.85 was adopted as the period reduction factor.

For Level 1 earthquake elastic design, the capacity of structural elements were designed according to the worst case load combination, and an importance factor of 1.1 was considered for load cases without earthquake. The main structural members were designed to remain elastic under level 2 earthquake. The seismic internal force adjustment was ignored in level 2 calculation. The load factor, material factor and the modified coefficient for seismic load capacity of elements were all taken as 1.0. That is to say, except for not considering the seismic internal force adjustment, the standard load combinations were used to check against the standard element capacity.

It is the Chinese seismic code design requirement that for each structural system it was necessary to apply the

Table 7. Seismic design target

| Earthquake Level | Level 1 | Level 2 | Level 3 |
|---------------------|-----------|-------------------|-----------------------------|
| Performance Level | No Damage | Repairable Damage | No Collapse |
| Storey Drift | h/500 | - | h/50 |
| Element Performance | Core wall | Elastic | Limited plastic deformation |
| | Diagrid | Elastic | Limited plastic deformation |
| | Others | Elastic | Limited plastic deformation |

Table 8. Comparison of seismic design parameters

| Design parameter | Seismic code provision | Seismic hazard study |
|------------------|------------------------|----------------------|
| Response coeff. | 0.080 (0.030) | 0.148 (0.381) |
| Char. period (s) | 0.350 (0.350) | 0.350 (0.450) |
| Damping ratio | 0.040 (0.040) | 0.040 (0.040) |

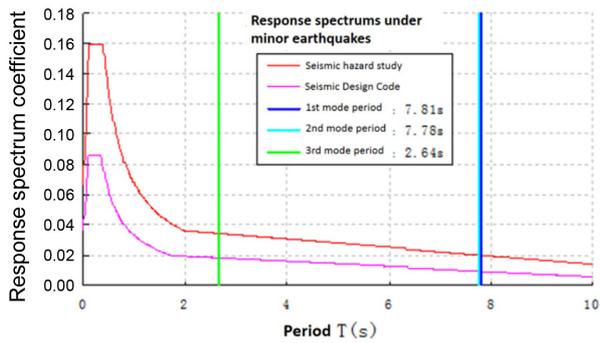


Figure 33. Comparison of response spectrums under minor earthquakes based on Chinese code and seismic hazard study.

internal force adjustments for the capacity checking of main structural elements.

In accordance with the provisions of Chinese seismic design code (GB 50011:2001), high-rise building structure is allowed to exhibit plastic deformation without collapse under Level 3 major earthquake to ensure life safety and safe evacuation. At such extreme event, the tower structure will behave nonlinearly and the redistribution of internal forces among structural elements will occur. Nonlinear structural analysis became necessary to carry out the quantitative assessment and to evaluate the

Table 9. Adjustment factors for seismic design

| Member | Action | Adjustment factor |
|-----------|-------------|--------------------------------------|
| Core wall | Moment | Base enhancement: 1.1 Others: 1.3 |
| | Shear force | Base enhancement: 1.9 |
| | Axial force | 1.0 |
| Diagrid | Moment | 1.7 |
| | Shear force | 1.7 |
| | Axial force | 1.1 |

structural global performance and the adequacy of the key structural elements. The results will be checked against the criteria defined for structural global performance and elements deformation based on the performance-based design approach and the displacement-based design procedures in order to achieve the over-arching performance objective of ‘No Collapse’ under major earthquakes.

Nonlinear time history analysis is the most advanced and comprehensive analysis procedure to evaluate the nonlinear seismic response of structures. It does not have the inherent limitation inherent of static pushover analysis. For Guangzhou IFC, non-linear time history seismic analyses were used for the evaluation of structural performance under Level 2 and Level 3 earthquakes. The software used was CEAP based on general software LS-DYNA developed by LSTC. The analyses were carried out using central difference history method with explicit

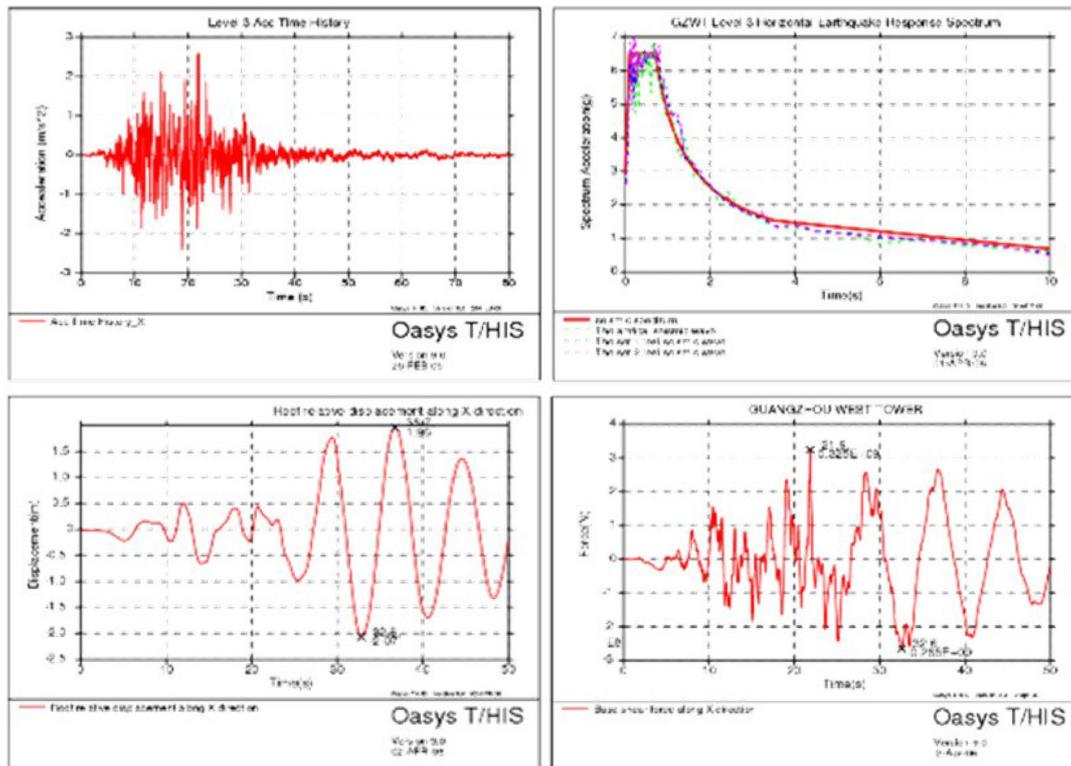


Figure 34. Nonlinear time-history analysis.

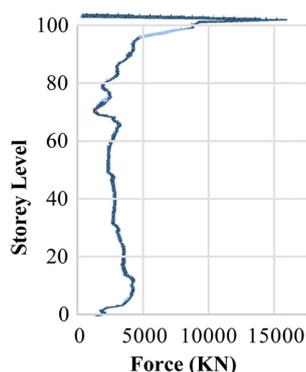


Figure 35. Storey shear force under level 3 earthquake.

integration.

Two-directional earthquake input were considered and applied at the nodes of the structural model and at the pile cap level as the base of building. The earthquake input direction was applied along the deformed direction of the first and second modes of the building structure. The earthquake wave spectrum used were at ground level and were obtained from the site-specific seismic hazard assessment study.

Structural safety evaluation for major earthquake was reviewed under two aspects, namely the structural global performance and the elements deformation performance. Evaluation of global performance was based on elasto-plastic inter-storey drift ratio, ratio of shear force to building weight, displacement time history against shear forces at the top and bottom of structure, development sequence of plastic deformation in key areas. Evaluation of structural members were carried out by checking elements' plastic deformation results against the limits defined by performance criteria.

Nonlinear static pushover analysis was a simplified seismic analysis procedure. Strictly speaking, pushover analysis was only suitable for relatively stiff structures within short to medium period range for which the fundamental mode dominates the structure's dynamic seismic response. For flexible, long period structures such as tall buildings, there are inherent deficiency and limitation with respect to the ability of this simplified non-linear analytical method to account for the effects of higher modes. Difficulties arose in assuming a pattern or a few possible patterns for the vertical distribution of the applied horizontal force that could accurately account for the effect of higher modes in flexible structures. It is prudent that the seismic performance evaluation of Guangzhou IFC under various levels of design earthquakes were primarily based on the results of non-linear time history analyses, and the results obtained from static pushover analysis only served as supplementary reference in this project.

In order to more accurately consider higher mode effect in static pushover analysis, the improved patterns recom-

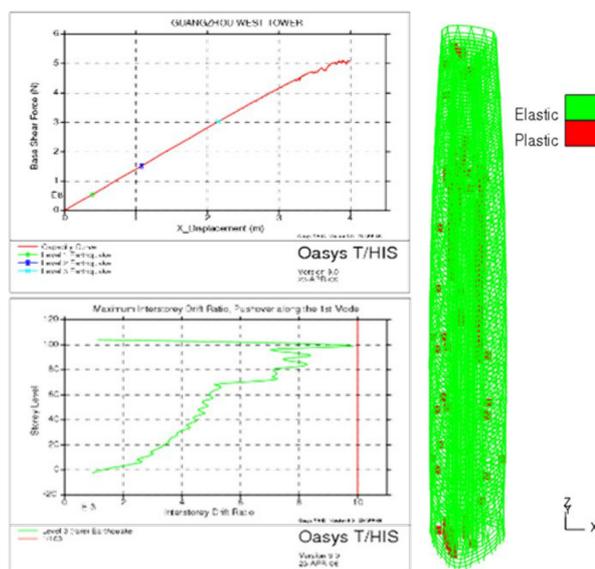


Figure 36. Nonlinear static pushover analysis.

mended by FEMA 356 for vertical distribution of applied horizontal forces at floor diaphragms were adopted. FEMA 356 suggested that such pattern should be used for buildings with a fundamental period exceeding 1.0 second. The vertical distribution of the applied horizontal pushover forces was proportional to the storey shear distribution calculated by the response spectrum analysis that included sufficient modes to capture at least 90% of the building's total participating mass. Two sets of elastic response spectrum analyses were carried out using ETABS and SAP 2000 structural models. The earthquake input was represented by the Chinese Code Level 3 seismic response spectrum and was applied along the directions parallel to the first and second modes. In each elastic response spectrum analysis, the inter-storey shear forces for all storeys were obtained from ETABS. The horizontal pushover force applied at a floor diaphragm was then calculated by the difference between the inter-storey shear forces above and below the floor diaphragm under consideration. The horizontal pushover forces obtained at all floor diaphragms determined the pattern of the vertical distribution of the horizontal applied forces.

Due to the unconventional structural diagrid system adopted and the fact that the building has exceeded the local code design limits, large-scale experimental physical tests were carried out in addition to the analytical models, in order to verify the design assumptions and performance predictions. Two independent shaking table tests of the scaled physical models of the super-tall tower were conducted in Beijing and Shenzhen respectively.

7.5. Nonlinear Stability Analysis

The traditional stability analysis method considered strength and stability separately in the analyses with the



Figure 37. Shaking table test.

Table 10. Buckling modes of building

| Mode | 1 | 2 | 3 | 4 |
|-----------|--------|--------|--------|--------|
| λ | 13.900 | 14.023 | 14.114 | 15.238 |

| Mode shape | 1 | 2 | 3 | 4 |
|------------|---|---|---|---|
| | | | | |

conception of effective length. However, in some cases the effective length method may not reflect the true interdependence of stability load carrying capacity between structures and members. For example in the Code for Steel Structure Design (GB 50017-2003), the calculation of members buckling assumed that structural columns at the same floor buckle symmetrically or asymmetrically at the same time with the same mode.

In the calculation of member stability load carrying capacity, the global structural stability was almost given with the effective length method. But in reality, an individual or a few members will first buckle elasto-plastically. Moreover, the effective lengths of different structural members were sometimes very difficult to be calculated accurately. If the effective lengths were calculated without considering structural offset or not from a global structural viewpoint, it may potential give unsafe results. When subjected to a combination of loads of wind, earthquake and gravity, unavoidable internal forces and displacements were induced in the structure, and the structure will response with geometrical nonlinearity. Therefore, second-

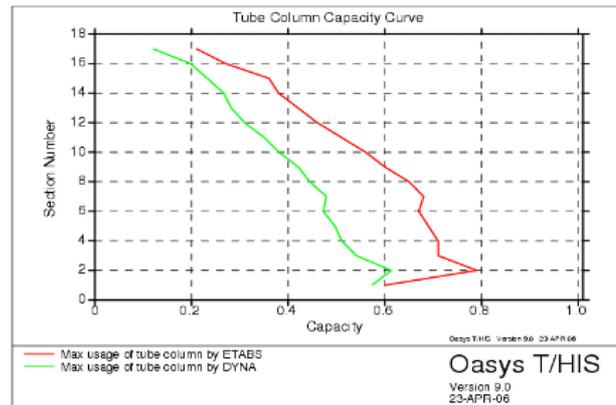


Figure 38. Comparison of diagrid column section utilization based on effective length method and nonlinear analysis method.

order effect will need to be considered in the calculation. To summarize, a stability check completely based on the traditional analytical method was not enough, and nonlinear stability analyses were deployed as comparison to complement the results.

From a nonlinearity point of view, strength and stability were always interdependent. By nonlinear analysis, the structural load-displacement curve of the whole process will show the progression in the change of strength, stability and stiffness clearly. The following factors were considered in the nonlinear analysis method:

- Influence of structural deformation, including the stiffness reduction effect due to axial force (geometrical nonlinearity).
- Influence of structural imperfections, including global structural imperfections and member initial imperfections (including residual stresses).

The actual structure was different from the perfect model because of the influences of various fabrication and construction imperfections. For structures sensitive to imperfections, the imperfections may degrade the structural stability rapidly, so it was necessary to consider the influence of random parameters and to carry out sensitivity studies on structural stability. The random imperfections were mainly classified into three types:

- Uncertainty of physics and geometry: such as material properties (elastic modulus, yielding stress, Poisson's ratio), member size, sectional area, residual stress, initial deformation, etc.
- Statistical uncertainty: when counting physical quantity and geometrical quantity relative to stability, the probability density distribution function was chosen according to limited samples, so it was with experience to some extent. This kind of uncertainty were called statistical uncertainty.
- Model uncertainty: in order to analyse the structure, various factors were difficult to considered in the cal-

culatation such as assumptions, mathematical model, boundary conditions and the current technical level, which caused difference between the theoretical value and the actual load carrying capacity, which was due to model uncertainty.

7.6. Node Design

The external diagrid was a shell-like three-dimensional system composed of steel tube concrete columns that inter-crossed hyperbolically with the steel beams at each floor. The steel columns and steel beams were connected at nodes. The number of node joints were large and their sizes were substantial. Since the stress distribution at the nodes could not be directly reflected in the global model, and given the complexity of the joint configuration and its importance to the structure, it was necessary to carry out further finite element analysis of the nodes to ensure that they would work near to the elastic regime, that stress concentration phenomena was not significant so as to suppress brittle failure and to ensure that the nodes satisfy code and safety requirements.

The stress analysis of joints was carried out with the software NASTRAN widely applied in aviation and air-space fields. In addition, for both the mid-level and low-level nodes, the envelope case of maximum compression, maximum tension and maximum bending were input as force boundary conditions to carry out the analysis to obtain finite element analysis results of typical steel external diagrid node.

For steel material, the von-mises yielding principle in elastic-plastic mechanics (namely the fourth strength theory) was used. When the shear stress of the spatial octahedron equalled the yielding stress under uniaxial tension, steel would be in the plastic state. It was obtained by checking the structural strength for the event that even in linear elastic design, local plastic deformation was allowed, but the plastic deformation range and the degree of stress concentration was limited. If the stress concentration coefficient was assumed as 2.0 and the member was working at an internal force 80% of its ultimate load carrying capacity, the ratio of maximum von-mises stress to yielding stress would be 1.6. Therefore the safety of the members were evaluated based on the stress concentration areas and stress concentration coefficients obtained from linear elastic analysis. Because the steel actual yielding strength would be about 1.1 to 1.2 times of its characteristic value, the area where the stress concentration coefficient was less than 1.2 would be considered to be in a quasi-elastic state and without plastic deformation. It is necessary to note that the above method was based on the premise that von-mises yielding principle was satisfied. If the member was under tension in three directions, the von-mises principle is not applicable fail and the structural failure could be brittle. For this scenario, the first strength theory would be applied (maximum tensile stress strength theory) or the method in fracture mechanics should be

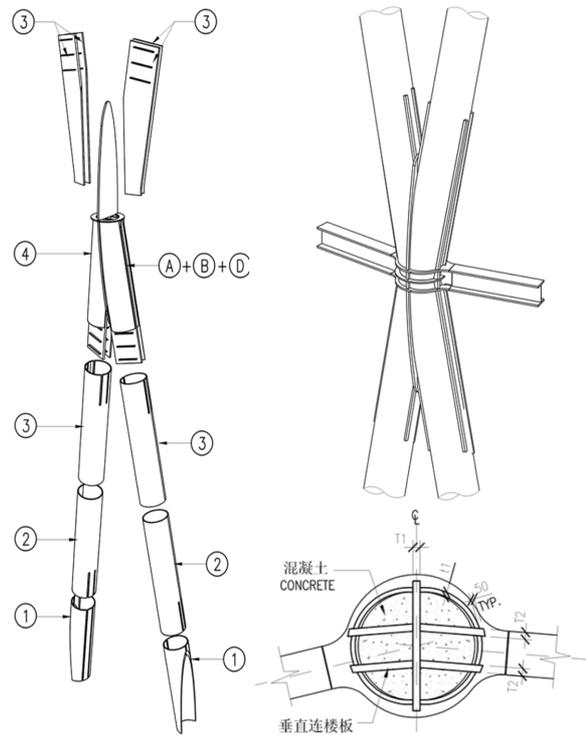


Figure 39. Diagrid node assemble.

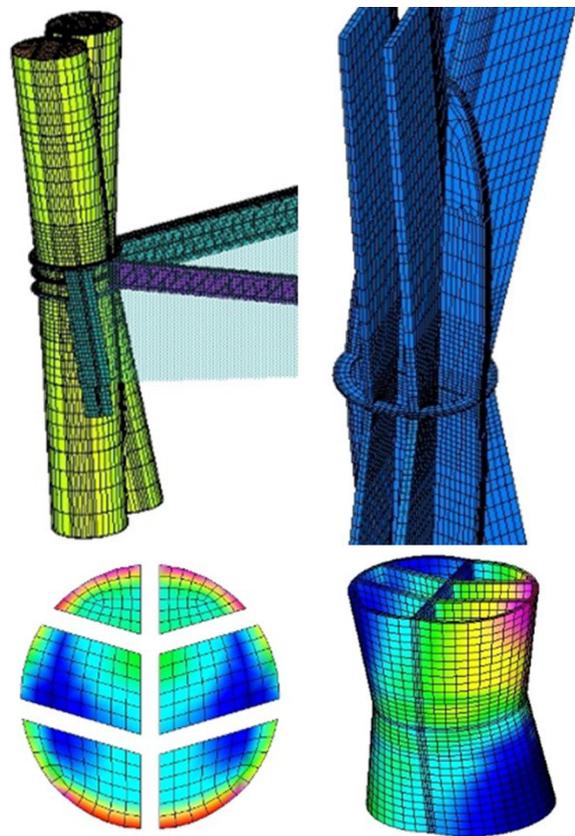


Figure 40. FE modelling of nodal connection.



Figure 41. Large-scale testing of nodal connection.

explored.

The stress analysis results concluded that when diagrid columns were under ultimate load and thus completely plastic, the joints basically remained quasi-elastic. The joints area would become plastic, but the plastic area was controlled not to develop excessively, and that the joints were considered as strong joints.

For concrete material, the stress state in question was when it was under three-dimensional compression and comparing with the strength of restrained concrete. The concrete could be assumed to be intact under three-dimensional compression only if the maximum compressive stress was less than the restrained concrete strength. Because of the complex 3-D constitutive relationship of concrete, a physical joint testing was carried out to further check and verify the safety of the joint and ensure that the joints were stronger than the members.

7.7 Floor System

The choice of floor structural system was related to the global structural system, architectural planning, building services routing and floor headroom. Being tall and having lots of storey, this building required the floor to be as light as possible. This reduced the size and mass of the core and columns needed, and reduced the seismic response during earthquake. This also reduced cost and time of construction, and made the building more efficient in terms of usable floor area. However, the requirements of achieving high clear headroom for floors limited the height of structural zone in the floor system, and required close coordination with architecture and building services. Also, the tight construction schedule also needed to be taken into consideration. Composite floor system with steel beam was chosen to cater for the various considerations.

The typical beam spans for the tapering building ranged from 8 to 13.5 m. The slab thickness was set at 130 mm for office and hotel levels in general, with thickening to

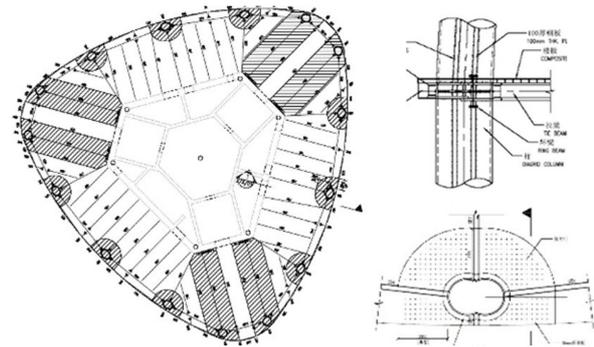


Figure 42. Strengthening at node floor.

suit other functions such as mechanical services when applicable. The use of steel beams reduced the tower overall weight, and facilitated the fast-track construction and connected well with diagrid columns. The reinforcement in the composite floor slabs extended into the exterior wall of the central core for anchorage. The shear studs were used to combine floor slabs and steel beams for composite action. Under earthquake and wind loads, these measures were to ensure that the perimeter diagrid tube structure and the central core resisted horizontal loads together and at the same time provided lateral restraint for the perimeter diagrid columns.

As the diagrid columns endured vertical loads (including those due to lateral loads) and the compressive force within the section created an outward resultant force at the node point. On plan, the ring beams, tie beams and floors were directly connected with columns. Steel beams were connected with columns through the whole section and the tensile capacity of steel beams could be fully exerted. Where the floors were connected with column nodes within the close proximity, namely areas around the column perimeter, the tensile capacity of reinforced concrete slab sections may not sufficient in transferring the outward node forces, additional steel plates were added to strengthen and to transfer the node forces. The lateral node forces could be calculated with the simple static forces equilibrium. The largest lateral forces occurred at the base of the building where the axial forces in the columns were greatest and near the corner where the change in angle was greatest (4 degrees approximately).

7.8. Shrinkage and Creep

Because of the difference in material used between the central core and the external diagrid column tubes, differential axial compressive shortening would be expected. For super high-rise buildings, the influence of the differential deformation between the core and perimeter system could be very significant regardless of whether they were elastic or inelastic. It had to be specially considered in the design and construction.

The restraints of concrete shrinkage and creep in the

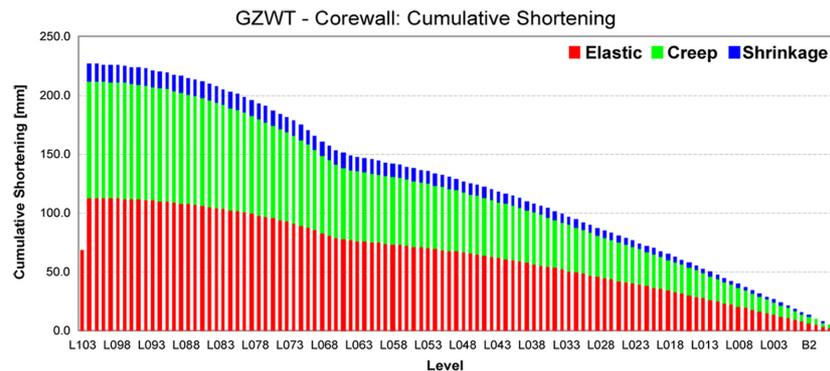


Figure 43. Long-term deformation of core wall.

central core under gravity load were enhanced because of the differential shrinkage and creep with the external diagrid. The restraints reduced the load on the concrete core and increased the load on the external diagrid. Meanwhile the stress in steel beams connecting to the external diagrid increased locally at the connections.

Axial compression of the vertical central core due to concrete shrinkage and creep in anaphase could cause the floor height in the lower levels to decrease. This issue not only affected the non-structural installation, but also influenced the elevator utilization that required strict level height, especially for the project that adopted double-deck elevators.

To compensate the adverse effects of long-term creep and shrinkage, the following measures were applied:

- Strict control of concrete manufacture techniques were enforced to minimize material creep. Proper concrete mixing proportion were determined by tests and thereby to calculate shrinkage and creep in the construction and service stages.
- The connection of the steel beams to the central core and the external tube were effectively pinned to minimize the impact of concrete shrinkage and creep of the core.
- The compressive stress level on the concrete core was closely controlled. Embedded structural steel sections would be considered in the wall to increase the steel reinforcement ratio where appropriate.
- Fill material with good elasticity and ductility was adopted for connection between structural members.
- For unavoidable deformation such as elastic and long term deformation of concrete, pre-set in floor levels were adopted in the construction stage to ensure that sensitive equipment such as elevators can be installed function properly.
- In the construction stage and service stage, a complementary deformation monitoring system was implemented to allow adjustment on the pre-set value where appropriate according to the actual data obtained during construction.



Figure 44. Climb-form system of central core.

- The reinforcements in floor slabs were laid in two directions and double layers with adequate reinforcement ratio.

7.9. Construction Aspects

The central core structure was readily constructed in reinforced concrete using a climb-form system. In-situ reinforced concrete was used in the core because of great structural stiffness, high fire resistance with a low initial cost as well as low maintenance expenditure. It was the first project in China to adopt grade 80 high strength concrete for wall elements. The control of temperature rise and gradient was important in the construction phase to ensure the concrete quality.

The external diagrid steelwork was prefabricated into



Figure 45. Prefabricated diagrid steelwork.



Figure 46. Construction phase of main tower.

individual units each weighing within 30 tonnes for practical transportation to site and for lifting in position. While the internal stiffening of diagrid nodal joints was carried out and tested under control environment in the factory, the assemble units in the form of x-joints with attaching column tubes were prepared for standardized site welding and splicing which facilitated efficient erection on site.

With the construction-led design approaches adopted by Arup and the state-of-the-art construction techniques, a floor construction cycle of two days was achieved which was record-breaking in China.

8. Conclusion

The Guangzhou IFC, being one of the new landmarks located in the strategic business area of Pearl River New Town District in Southern China, set forth an excellent example of advanced engineering design of modern tall buildings. Following Arup's total design philosophy for sustainability, multifaceted engineering solutions were developed to a high level of efficiency and facilitated cost-effective construction of the super-tall tower.

References

- Alostaz, Y. M. and Schneider, S. P. (1996). Connections to concrete-filled steel tubes. *Structural Engineering Series 613*. University of Illinois at Urbana-Champaign.
- Fam, A., Qie, F. S., and Rizkalla, S. (2004). Concrete-filled steel tubes subjected to axial compression and lateral cyclic loads. *ASCE Journal of Structural Engineering*, 130(4), pp. 631-640.
- GB 50011:2010. (2010). Code for seismic design of buildings.
- Mele, E., Toreno, M., Brandonisio, G., and de Luca, A. (2014). Diagrid structures for tall buildings: case studies and design considerations. *The Structural Design of Tall and Special Buildings*, 23, pp. 124-145.
- Moon, K. S. (2008). Sustainable structural engineering strategies for tall buildings. *The Structural Design of Tall and Special Buildings*, 17, pp. 895-914.
- Shen, Z. Y., Wang, W., and Chen Y. Y. (2009). Recent development and applications of tubular structures in China. *Proceedings of the 12th International Symposium on Tubular Structures*, Shanghai, China, 8-10 October 2008, pp. 305-312.
- Wilkinson, C. (2012). Guangzhou Finance Centre: An elegant simplicity of form. *Proceedings of the CTBUH 9th World Congress*, Shanghai, China, 19-21 September 2012, pp. 386-390.