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Innovative Technologies and Their Application on the Construction of a 100-Plus-Story Skyscraper

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Abstract

Experience on the construction of several 100-plus-story skyscrapers including Guangzhou West Tower, Guangzhou East Tower, and Shenzhen's KK100 is described considering the increasingly strong development trend of 100-plus-story skyscrapers in China. Difficulties in the construction of 100-plus-story skyscrapers are investigated. Four innovative construction technologies receive detailed descriptions: intelligently and entirely-jacked work platforms, formwork and suspension scaffolding systems ("jacking and formwork systems"), multi-function low-carbon concrete, 5D-BIM ("five-dimensional building information modeling"), and safe and rapid vertical transport, as they have found successful applications in actual projects. Popularized systematically as technical achievements, these technologies will significantly influence the construction of similar projects in the future, and produce more social and economic benefits.

Keywords: Construction of 100-plus-storey skyscraper, Jacking and formwork system, Multi-function low-carbon concrete, 5D-BIM, Vertical transport technology

1. Foreword

In recent years a lot of tall buildings have been built in China (Lie et al., 2012; Zou et al., 2014). The construction of many 100-plus-storey skyscrapers in China in recent years results in the rapid improvement in Chinese construction technologies. Cutting-edge technologies as well as state-of-the-art equipments are used in the construction of these 100-plus-storey skyscrapers. In this sense, these buildings typically reflect the comprehensive strength including the innovation capacity of Chinese construction industry.

Difficulties in the construction of 100-plus-storey skyscrapers include complex site conditions, stringent requirements on safety and quality, and complex technologies. The difficulties are thoroughly investigated using the examples of the Guangzhou West Tower, Guangzhou East Tower, Shenzhen KingKey Financial Center 100 and others. Innovative technologies are abstracted based on experience in those projects.

2. Intelligent Work Platform, Formwork and Suspension Scaffolding System used for Super High-Rise Buildings

2.1. Difficulties in construction of the core tube of 100-plus-storey skyscraper

A 100-plus-storey skyscraper usually takes a unique shape with novel facades; it has a small built-up area but offers immense function diversity. Its core tube and outer frame-column tend to be vertically structurally complex and variable. Its shafts for vertical pipelines and elevators vary irregularly in shape. Arrangement of other pipeline features also provides enormous complexity. As far as the walls of core tube are concerned, transformation is often observed among stiff steel plate-reinforced walls, thick walls, thin walls, straight walls, oblique walls, and curved walls. Moreover, short construction period necessitates higher construction efficiency. Shown in Fig. 1 is the vertical structural variation of the core tube of Guangzhou West Tower.

2.2. Innovative jacking and formwork systems

The jacking and formwork system is innovatively developed to surmount the difficulties in core tube construction. It comprises the steel truss platform, jacking and supporting system, suspension scaffolding system, formwork system, and intelligent control system. Its features are perfect and safe work space, accurate quality control, fast construction speed, energy-saving and high efficiency [1].

Innovative design philosophies formulated against difficulties in high-rise building construction are "high-position for the work platform, low-position for the supporting points", "changing aerial work into work in a safe and closed space", "major loading structure of the work platform shall maintain sufficient strength even if it is erected aerially", and "adjustment to formwork shall remain easy aerially". Five innovations embody the philosophies, creating

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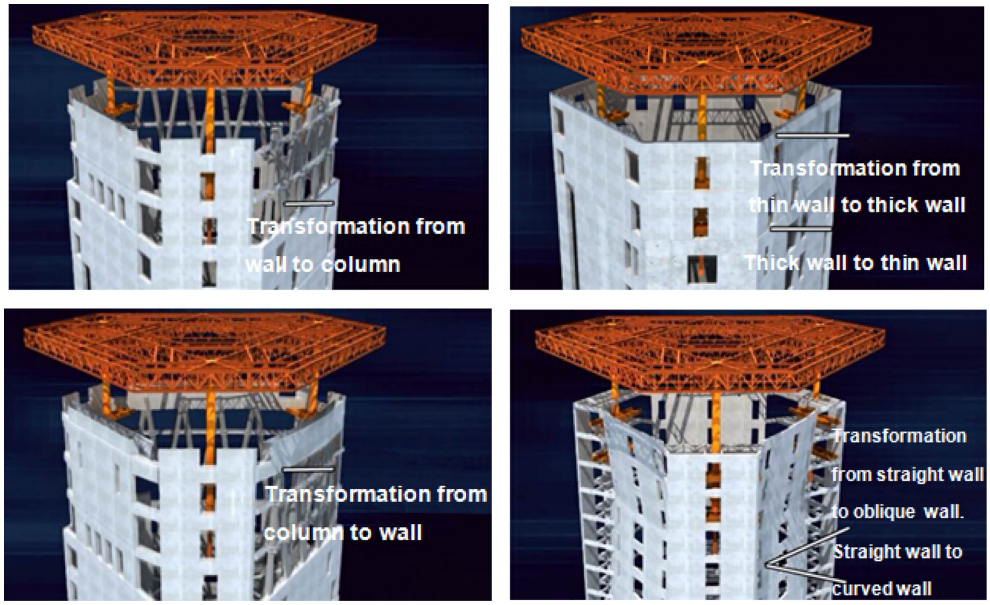


Figure 1. Schematic diagram of vertically structural variation of the core tube of Guangzhou West Tower.

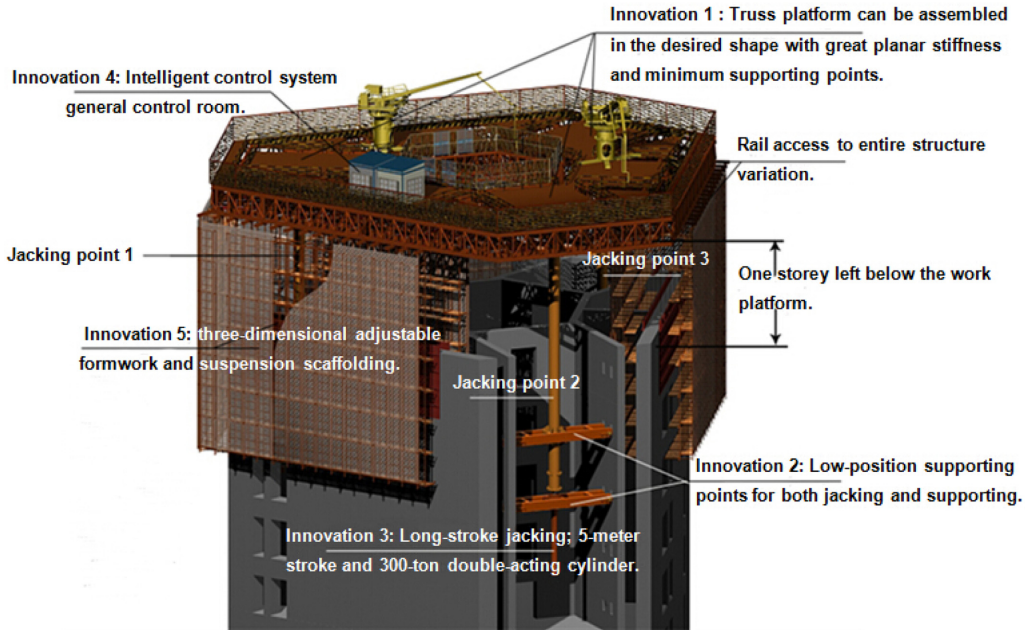


Figure 2. Facade effect diagram of the jacking and formwork system.

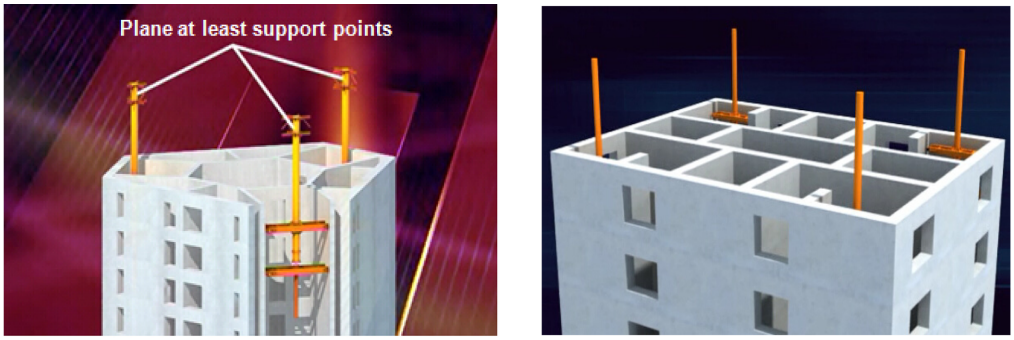
the construction speed of one storey per two days.

2.2.1. Minimum supporting points for the work platform

As an innovation, the work platform requires only three or four supporting points. By contrast, the conventional climbing framework requires about one hundred supporting points. Minimizing limitation by irregular structural variation on selection of supporting points, this innovation enhances adaptability of the jacking and formwork system to highly complex and variable structures. Without aerial modification, the system can climb until the top storey (Fig. 3).

2.2.2. Low-position points for both jacking and supporting

The supporting points for the platform are positioned generally two to three storeys lower than the storey currently under construction. This innovation is capable of



(a)Three supporting points forming virtually a plane (b)Four supporting points forming virtually a plane

Figure 3. Low-position and minimum supporting points for the work platform.

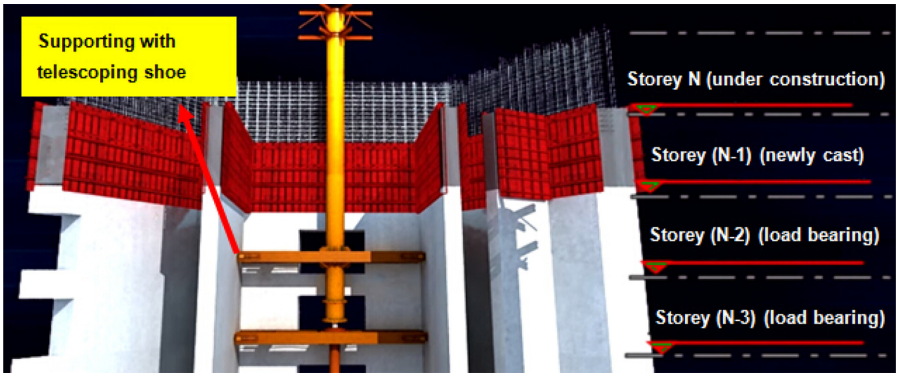


Figure 4. Low-position supporting points.

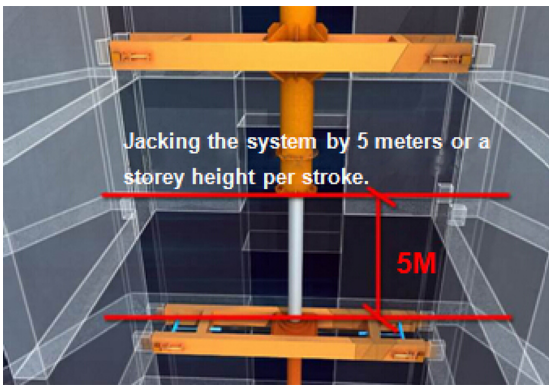


Figure 5. Schematic diagram of long-stroke jacking.

speeding construction progress by one day in comparison with conventional practice, where the jacking may not be performed until the concrete is sufficiently cured.

2.2.3. Long-stroke jacking

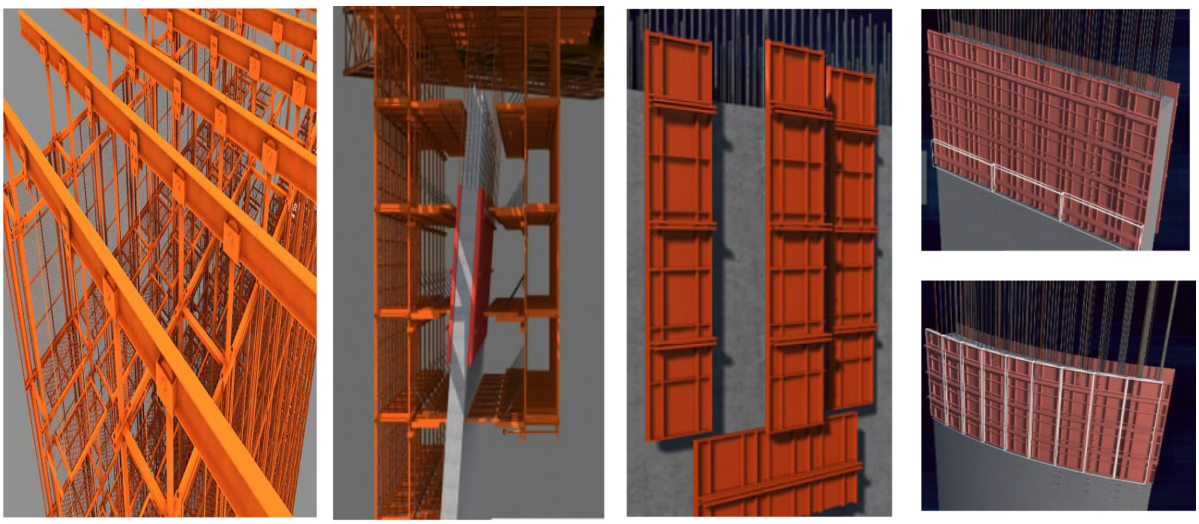
Long-stroke, large-capacity cylinders are employed, which individually can jack the formwork and suspension scaffolding system by one storey per stroke (5 meters within 2 hours. Fig. 5). A benefit is remarkable enhancement of jacking efficiency, compared to a conventional climbing formwork system, which has to climb 5 to 10 times and require one day to cover that distance.

2.2.4. Three-dimensional adjustable formwork and suspension scaffolding

Three-dimensional adjustable formwork and suspension scaffolding system enables the formwork and suspension scaffolding to flexibly slide with structural variation of core tube, such as transformations from thick wall to thin wall, from straight wall to curved wall, and from wall to column. Adaptability of the formwork and suspension scaffolding system can thus be notably improved (Fig. 6).

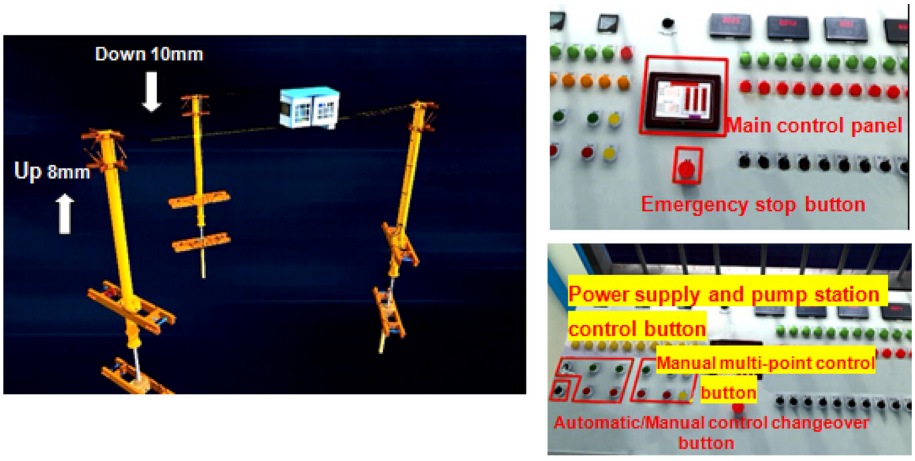
2.2.5. Intelligent control system

An intelligent control system is responsible for automatic control over the jacking and formwork system, such as automatic correction, adjustment, leveling and curving at a single or multiple points to ensure high stability and efficiency of construction. Automatic emergency stop conditions can be preset. An emergency stop button and other features such as anti-falling are provided to ensure the safety of construction (Fig. 7).



(a) Adjustable suspension scaffolding (b) Hinged boards (c) Combination formwork

Figure 6. Three-dimensional adjustable formwork and suspension scaffolding.



(a) Automatic correction and adjustment (b) Control system

Figure 7. Intelligent control system.

3. Multi-Function Low-Carbon Concrete for 100-Plus High-Rise Skyscraper

3.1. Disadvantages of conventional super high-strength concrete and requirements on performances of innovative super high-strength concrete

Disadvantages of conventional super high strength concrete include low mobility, high viscosity, poor plasticity-retention performance, fast settlement speed, great heat from early hydration, severe early shrinkage, and rapid segregation under high pressure. However, requirements on super high-strength concrete used in the construction of high-rise buildings are high mobility, low viscosity, excellent plasticity-retention performance, slow settlement speed, slow adiabatic temperature rise, low early shrinkage and no bleeding under high pressure. Taking these disadvantages into account, the research team has successfully developed the multi-function low-carbon concrete to meet these requirements, which is notable for high strength, high stability, high pumping performance, low heat, low shrinkage, low cost, self-curing, self-compaction and self-leveling [2].

3.2. Performances of multi-function low-carbon concrete

3.2.1. High strength, high stability and high pumping performance

Technologies of super-low water-to-gel ratio, optimized aggregate gradation, and powder gradation are adopted to prepare C80-C120 high-strength concrete.



Figure 8. Performances of multi-function low-carbon concrete.



Figure 9. Super-height pumping.

Innovatively-developed carrier-type fluidizing agent (polycarboxylate water-reducing agent is mixed with naphthalene-based water-reducing agent to obtain high-efficiency water-reducing agent, which is further mixed with zeolite to obtain the carrier-type fluidizing agent) is used as an admixture to improve the dispersity, mobility and plasticity-retention performance of concrete and reduce the viscous resistance to concrete by the inner wall of pumping pipe to enable super-height pumping (Figs. 8 and 9).

3.2.2. Low heat, low shrinkage and low cost

In the preparation of concrete, environmentally-friendly low-cost raw materials are used; for example, fly ash, microspheres and a tiny amount (1% to 2%) of expansion agent. A substantial amount of cement and mineral powder may be replaced by fly ash and microspheres, with the reduced heat from hydration, therefore the amount of cement needed can be significantly reduced. Zeolite which is good at water absorption and retention is used to suppress the early self-shrinkage of concrete. The concrete with low heat and low shrinkage suitable for stiff steel plate-reinforced walls can be prepared.

3.2.3.Self-curing, self-compaction, and self-leveling

Using the carrier-type fluidizing agent, retard water release is achieved to furnish 4-hour plasticity retention, ensuring uniform internal water supply in concrete, thus removing the need of external water sprinkling for curing.

The new-type of thickening agent (zeolite), aggregates with optimized gradation and microspheres are innovatively utilized. The "rolling and sliding effect" of the microspheres and the "seamless filling performance" of the powders are borrowed to improve the cohesive strength and mobility of concrete. Benefits are self-leveling and uniform compact filling of concrete between moulds and in cavities (Fig. 10).

3.3. Performance indicators of multi-function low-carbon concrete

The performance indicators of concrete suitable for the construction of 100-plus-storey skyscraper given in Table 1 are obtained through nearly ten thousand tests and necessary theoretic analysis.

3.4. Innovation of super-height pumping

In the case of conventional pumping, reverse flow of concrete and blockage in the pumping pipe often occur due to super great height of the constructed structure and the immense weight of concrete in the pumping pipe.

Relation between the weight of concrete and the frictional resistance of concrete by the inner wall of pumping

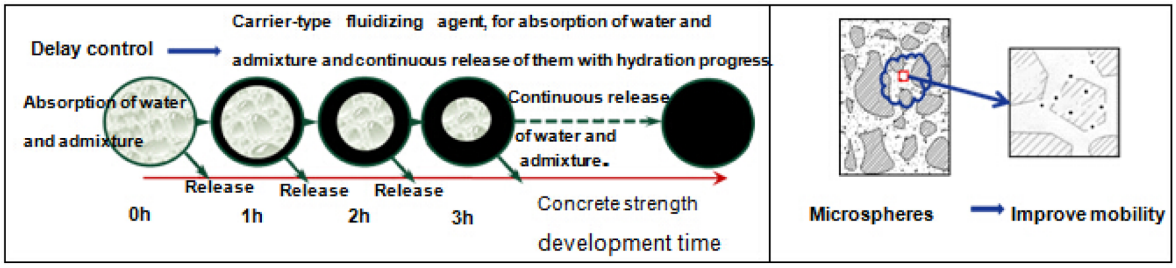


Figure 10. Schematic diagram of delay control.

Table 1. Performance indicators of multi-function low-carbon concrete

Concrete performance indicator	Concrete strength development time.				
	1h	2h	3h	4h	After pumping
Slump	> 220 mm	> 210 mm	> 210 mm	> 200 mm	> 180 mm
Extension	> 600 mm	> 590 mm	> 580 mm	> 560 mm	> 500 mm
Dumping time	< 8 s	< 8 s	< 10 s	< 10 s	< 12 s
U-shaped box test	≥ 320 mm	≥ 310 mm	≥ 300 mm	≥ 290 mm	≥ 280 mm
Plasticity-retention period			≤ 4 h		
Pre-settlement period			≥ 8 h		
Final settlement period			10 ~ 12 h		
Bleeding under pressure			0		
Temperature rise at low heat			< 75°C		

pipe based is formulated based on experience and theoretical analysis. The optimized workmanships are illustrated in Fig. 11.

(1) For offsetting the influence of concrete weight in vertical pumping pipes, horizontal pumping pipes at the length of 1/5 to 1/4 those of the vertical pumping pipes are arranged;

(2) Two cut-off valves are arranged in horizontal and vertical pumping pipes to locally offset the influence of concrete weight.

4. 5D-BIM Technology

Currently in most cases, the BIM technology applies only to a single or several construction activities with little mutual relevance, such as 3D visualized construction instruction, clash detection, solution optimization, and quantity calculation. Consequently, the BIM system cannot operate efficiently. The BIM technology has not yet been applied to the real-time analysis and management of the process, progress and cost of construction.

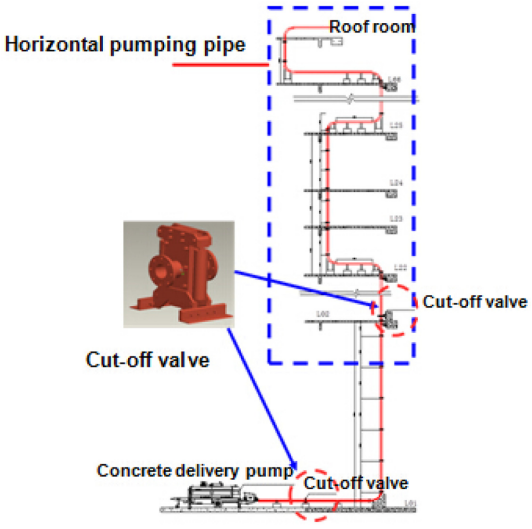


Figure 11. Schematic diagram of super great height pumping.

4.1. Formulation of modeling rules

Uniform modeling rules regarding civil work, steel structure and MEP (Mechanical, Electrical & Plumbing). The minor building information models of individual specialties can be integrated into a major building information model to be applied to project management.

(1) Uniform system of coordinates and initial point;

(2) Standardized rules on designations and definitions of structural members;

(3) Such attributes as building number, storey number and specialty title, assigned to each structural member.

4.2. Establishment of information platform

Huge volume of data may be shared via the BIM information platform, for design optimization, change management, node optimization, progress management, work face management, inter-specialty clash management, contract document management, and operation and maintenance management, to improve the detail sufficiency of general contract management (Fig. 12).

4.3. Real-time analysis and management of construction progress

A highly-feasible construction plan is automatically devised, taking into account the required quantities of workers, materials and machines as well as the required construction period, and referring to the work efficiency quota library and the quantities of construction. The actual construction progress is recorded and compared with the planned one. Construction progress warning activation conditions are set for each construction process and associated processes. In this manner, the construction progress is effectively managed.

4.4. Real-time analysis and management of cost

The quantities of construction are automatically calculated. State or enterprise-specified quotas are attached to the BIM model for construction cost estimation and control. Comparisons in three aspects: basic construction investment estimation, design budget estimation and budget estimation according to working drawings, cost market penetration analysis and solution cost optimization are

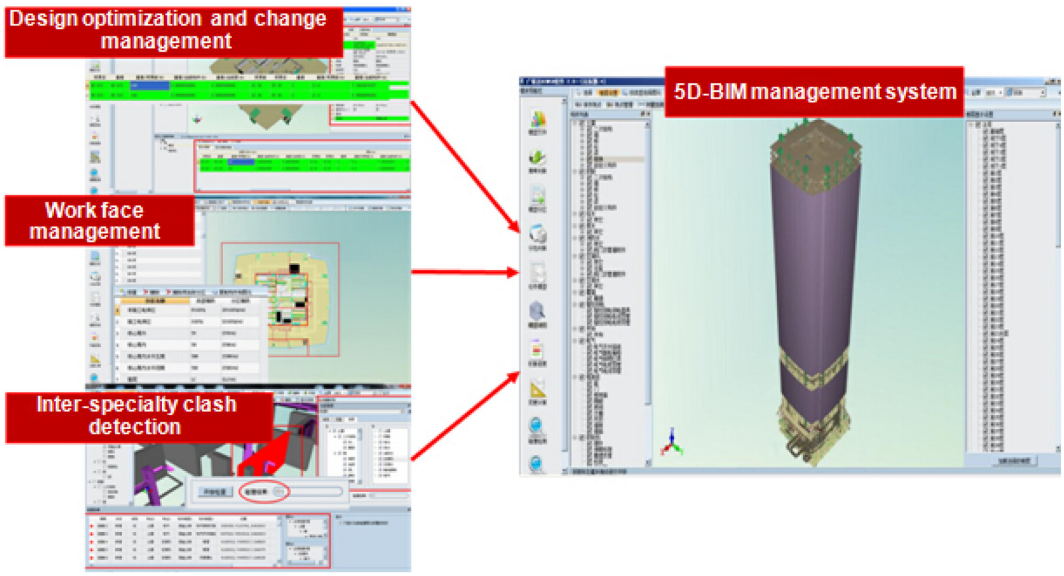


Figure 12. 5D-BIM management system.

performed via the BIM model.

4.5. Formation of central database

5D virtual construction is performed using the BIM technology, to enhance the on-site construction progress and cost management. General control analysis and management are performed via the central database of CSCEC4 in Guangzhou, to establish the performance library and quota library (Fig. 13).

5. Safe and Rapid Vertical Transport

Currently problems with vertical transport in the construction of 100-plus-storey skyscraper include reduction to construction efficiency, hindrance to construction progress, and grave safety risk. To address these problems, the research team has invented the technology of safe and rapid vertical transport. Benefits offered by the technology are increased safety, stability and efficiency, and reduced energy consumption. The technology can meet the requirements on vertical transport imposed by structurally innovative structures.

5.1. Stable support for mega self-climbing tower crane

Possibility exists that the upper portion of the core tube of 100-plus-storey skyscraper, due to transformation from thick wall to thin wall, is incapable of supporting the mega tower crane. Verification calculations shall thus be

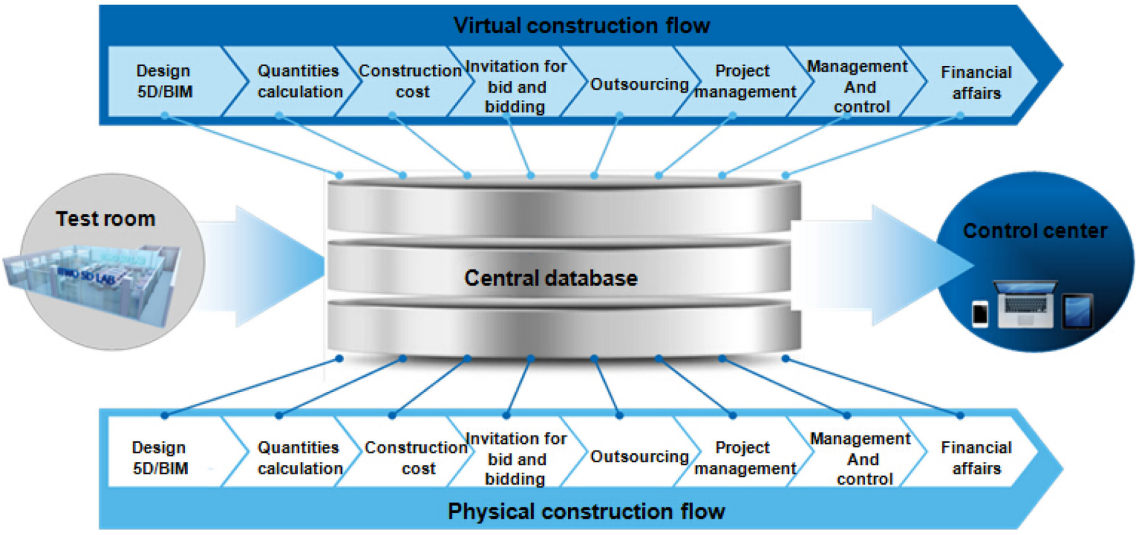


Figure 13. Central database of CSCEC4.

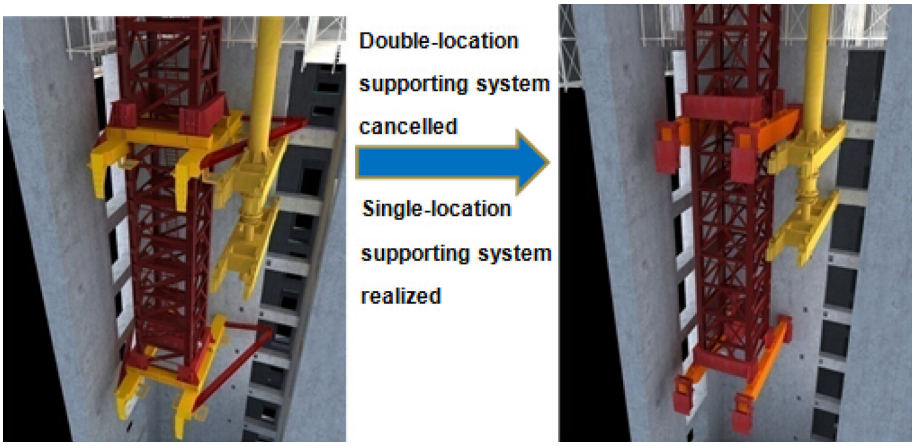


Figure 14. Single-location supporting system.

performed for the walls in question, and necessary reinforcement measures shall be taken. High stability of the mega tower crane itself shall be provided. Loads on the supporting points for the mega tower crane shall not exceed the limits. In this manner, the operation safety is effectively guaranteed.

5.2. Assembly and disassembly of the mega self-climbing tower crane

A single-location supporting system easy to be installed and removed is used for the mega self-climbing tower crane, which is also equipped with a self-assembly and disassembly system. Replacement of the conventional double-location supporting system with the bolting-connected single-location supporting system can facilitate the assembly and disassembly of the tower crane (Fig. 14).

The single-location supporting system results in construction efficiency and safety improvement. An example was the project of Shenzhen KingKey Financial Center 100, with the construction period was shortened by 54 days and the capacity of hoisting enhanced by 8100 cycles owing to the single-location supporting system.

5.3. Disassembly of the mega self-climbing tower crane

Should the mega self-climbing tower crane be disassembled at a time, serious risk could exist. An innovation aimed at high efficiency and safety of disassembly is installing a medium tower crane to disassemble the mega self-climbing tower crane, then installing a small tower crane to disassemble the medium one, finally disassembling the small tower crane.

5.4. High-efficiency transport by elevator used for construction

Conventional elevators used for construction, subject to restriction regarding safe attachment distance, cannot travel all the way to the storey under construction. Elevators with two standard sections and three tower as one employed. In a safe and efficient manner the elevators can take workers and materials directly to the storey under construction.

The technology has made excellent achievements. In the project of Guangzhou East Tower, around 18,000 man-days and approximately RMB 3.6 million were saved owing to the use of this technology.

6. Conclusions

To surmount the difficulties in the construction of 100-plus-storey skyscrapers, a series of innovative construction technologies are developed based on experience and through specific researches. Being socially and economically excellent, these technologies contributed heavily to the successful completion of some projects. The critical technologies among them have been applied to the representative 100-plus-storey skyscrapers such as Guangzhou East Tower (or Guangzhou Chow Tai Fook Center, 530 meters), Shenzhen KingKey Financial Center 100 (441.8 meters), Guangzhou West Tower (or Guangzhou International Finance Center, 440.75 meters), Chongqing World Financial Center (338.9 meters) and Twin Towers Guiyang (406 meters).

Systematic and detailed introduction to the critical innovative construction technologies are introduced based on experience and practice. These technologies are expected to exert great influence on similar projects. Application of these technologies can be made in the construction of high-rise buildings in the future.

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