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Significant Progress in Construction Equipment of Super High-Rise Building

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Abstract

The construction of rapid developing super high-rise buildings constantly faces great challenges and the innovation of construction equipment is a focus of these challenges. In this paper, three new inventions including the operation platform, tower crane and hoist are put forward around two of the most important issues of super high-rise building construction: vertical transportation and operation environment. Study background, composition of the equipment, working principles and key technologies are introduced in sequence. In the end, the paper summarizes the main problems in the further development of construction equipment.

Keywords: Super high-rise building, Construction equipment, Vertical transportation, Integrated platform

1. Background

At the forefront of building science and technology, the super high-rise building is of great significant in modern building trade. Great breakthroughs have been made in building function, structural system, building services and other aspects of super high-rise building. As soon as the construction process is concerned, however, intensive labor, low level of mechanization, long construction period, high cost and environmental pollution still restrict the industrialization level and comprehensive benefits.

Construction innovation usually focuses on materials, equipment, method (process) and management. Equipment innovation lags to other issues and it also greatly limits development of method (process) and management innovation.

There are two most important issues concerned with super high-rise building construction: vertical transportation and operation environment. Too many materials, components, labors and equipment should be transferred to high altitude, which is the core of improving construction efficiency. The traditional operation environment in platform is limited and inconvenient because of too many construction processes, great engineering quantity and operation requirements of super high-rise building construction. Improving operation environment is another key to increase construction efficiency.

From the start of super high-rise building in the end of the 19th century, turnover formwork, climbing formwork, sliding formwork, lifting formwork and jacking formwork were used in the construction of super high-rise building successively. These equipment combine formwork and scaffolding together to form closed and accessible environment. At the same time, material yard, tool room, placing boom, etc. can be installed on these formworks.

To improve vertical transportation, the tower crane and construction hoist were introduced to super high-rise building in the end of the 19th century in Europe, which greatly increase the capacity of the vertical transportation. Since then, the loading capacity, running speed and attachment were further studied. Nowadays, the tower crane is able to lift 100 t with maximum bending moment of 3200 t·m, while the load of hoist is over 3 t with a maximum running speed up to 120 m/min.

2. Integrated Platform

2.1. Background of the Study

Up until now, most super high-rise buildings beyond 300 m are designed in the form of a steel frame with concrete core-tube. Climbing formwork is most popular for the construction of core-tubes. But, it is often the case that the speed of core tubes fall behind that of the steel frame because of the anchorage of climbing formwork being located on new poured concrete. So the formwork must wait for the curing period of concrete before its climbing. In 2007, the jacking formwork was put forward in the construction of Guangzhou International Finance Centre (440.75 m). Low position bearing technic was adopted which support on the wall 2-3 stories below the pouring floor to release the restriction of concrete age. New bearing technic adopts two box beams and hydraulic cylinder bet-

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(a) Micro convex fulcrum



(b) Construction of Wuhan center

Figure 1. Micro convex jacking formwork.



Figure 2. Integrated platform in China Zun.

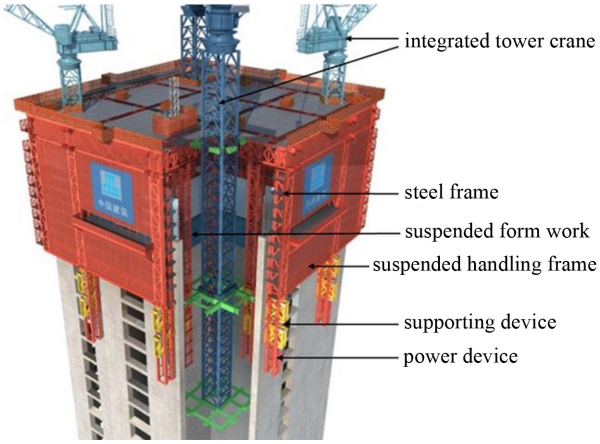


Figure 3. Composition of integrated platform.

ween them.

Box beam fulcrums have to rest on both sides of a tube, so the micro-convex fulcrum (Fig. 1(a)) was invented in the construction of Wuhan Center (438 m) in 2011 (Fig. 1(b)). This fulcrum only uses one piece of wall but the bearing capacity can be hundreds of tons. "Micro convex jacking formwork" involves more fulcrums distributed on the outer walls of core tube. Therefore, the bearing capacity and rigidity of formwork are further improved and it can integrate more facilities and be safer at height.

The next critical problem of formwork is the conflicts with tower cranes in layout and operation. Fixing tower crane directly on the platform or sharing supporting and power system of formwork with the tower crane are two different ways to solve the problem. Relatively speaking, the hoist and placing boom can be easily integrated into the formwork compare with tower crane. Due to the big improvement in integration, the new formwork is named as "integrated platform". A typical project adopting an integrated platform is China Zun (528 m) (Fig. 2).

2.2. Basic Introduction

An integrated platform consists of the following major parts (Fig. 3): steel frame system, supporting and power system, suspended handling frame, suspended formwork, integrated tower cranes and a monitoring system. Supporting and power system supports the integrated platform and jacks the formwork upwards. Steel frame installs all kinds of equipment and facilities and transfers the load to the supporting system. Handling frame was hung under the truss of steel frame. It provides operation space for concrete walls. Safety monitoring systems provide real time

monitoring of integrated platform to guarantee the safe operation.

An integrated platform usually owns 8 to 14 supporting units with a vertical load capacity of up to 600 t for one unit and in total about 5000 t for the whole supporting system. The high bearing (up to 600 t) and long stroke (up to 6 m) hydraulic cylinder was set in every supporting unit. Synchronous jacking takes only 2-3 hours to push the platform up to a new floor at a time.

The integrated platform covers the entire core tube with projected area over 1000 m^2 while spanning 4.5 floors in vertical with 10 operation levels. A steel plate installation, reinforcement assembling, formwork erecting, concrete pouring and concrete curing can be carried out simultaneously in the different operating layers.

Big operation spaces and great bearing capacity of integrated platform allow it to contain almost all the equipment and facilities, and construction technologies of the core tube, which can achieve the optimal allocation of resources and highly efficient construction. The hoist can reach to any levels of the integrated platform. The external transportation depending on hoist cooperating with the perfect inner one can realize the rapid flow of labors and materials.

2.3. Key Technologies

2.3.1. Supporting and Jacking System

Each supporting unit is composed of three major parts: micro convex fulcrum, supporting frame and hydraulic cylinder. The load of integrated platform was transfer to micro convex fulcrum through supporting frame. Micro convex fulcrum consists of bearing component, concrete micro-convex, black plate and tie rod. The supporting frame includes upper frame and lower frame. The hanging hooks of supporting frame act on the boot of bearing component to realize connection between supporting frame and micro convex fulcrum. The composition of the supporting and jacking unit is shown in Fig. 4.

There are three types of action including vertical force, horizontal force and bending moment. The vertical force is only resisted by the micro convex while the horizontal force will act on the tie rods, the bending moment will cause tensile force on the upper tie rod and compressive force on the concrete wall.

When the confined 2-3 cm concrete micro convex bears shear force, it will crack in direction of the bisector of the micro convex root angle. Before its cracking, the transverse deformation and crack propagation of concrete will be restricted by confining the steel plate. Therefore, the concrete in the damage position will be in states of three directional pressure, which help of the concrete to increase the bearing capacity and ductility significantly. Through theoretical and experimental study, the ultimate bearing capacity of single concrete micro convex is about 175 t. One fulcrum has eight concrete micro convexs and the design bearing capacity can reach 600 t.

The supporting and power system has three statuses including operation status, jacking status and lifting status. In operation status, part of the load is transferred to the upper frame and the other load is transferred to the lower one through the live cylinder. In jacking status, the load is transferred to the lower frame completely through the jacking cylinder. In lifting status, the load is transferred to the upper frame completely.

The bearing component and back plate are parts of the formwork and there are small grooves on the bearing component. After the concrete pouring, the micro convex fulcrum is formed automatically on the concrete surface. Several fulcrums are aligned on the wall, When the integrated platform passes the lowest fulcrum, it will be reused in the upper floor.

2.3.2. Platform Safety at Height

Taking advantage of the flexibility of micro convex fulcrum, a large span, multiple supporting units and overall anti-overturning steel frame which covers whole core tube

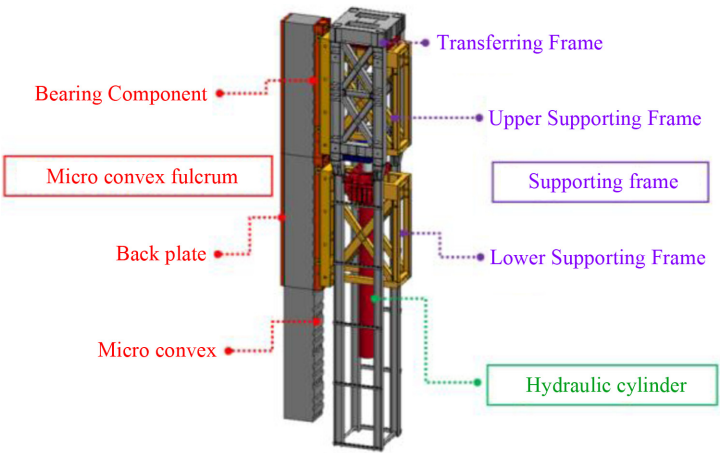


Figure 4. Composition of supporting and jacking unit.

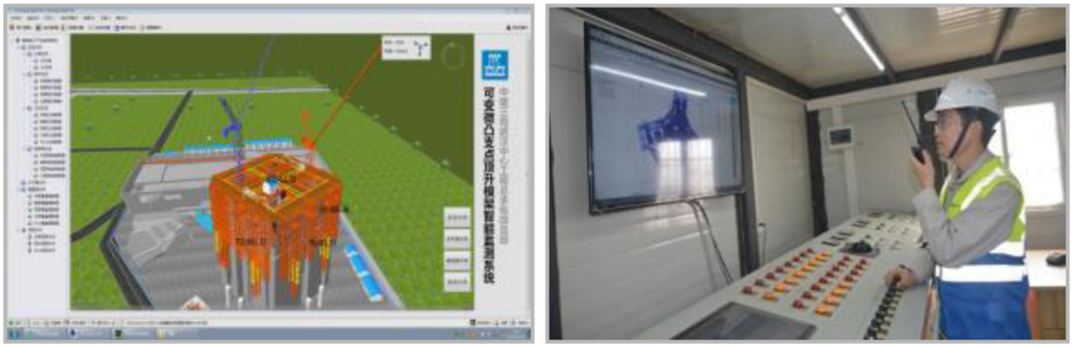


Figure 5. Monitoring system.

is established. The bearing capacity can be 2000 t or more and the structure can resist a class 14 wind.

To fit for the deflection of micro convex fulcrum caused by the construction error, a hook guide mechanism was invented by using a wedge boot of bearing component to help hook move into a bearing component automatically. To adjust the unbalanced force between different supporting units because of construction error, uneven stacking and jack error of cylinder, the disc spring device is put on the top of upper supporting frame, which can adjust hundreds of tons.

The monitoring system checks operating status of the integrated platform through various sensors, including strain, verticality, levelness wind speed and temperature. Monitoring software can collect, store, analyze and display the information fed back from the senses and send an alarm in advance (Fig. 5).

2.3.3. Integration of Tower Crane

Tower cranes in different level can be integrated into the platform from ZSL380, ZSL1150 to ZSL2700 (bending moment up to 2700 t·m). The small tower crane such as ZSL380 can be erected directly on the top of a steel platform.

As soon as the big tower crane is concerned, there are three tie-backs, the top tie-back is a screw jack fixed on the top of the platform and it provides horizontal support for the tower crane (Fig. 6). The middle and lower tie-back are fixed on tower crane mast and there are both puller cylinders and roller cylinders around mast. The middle tie-back is rest on the supporting system and transfer vertical load of tower crane to supporting system. Both middle and lower tie-backs transfer horizontal load to the concrete walls.

When the tower crane is working, release the top tie-back and push the lower and middle puller cylinders against the wall. The middle tie-back transfers both vertical and horizontal load while the lower tie-back transfers the horizontal load so that tie-backs could work together and resist the vertical, horizontal force and bending moment.

Before jacking up, people must balance the tower crane with weight so that its center of gravity is move to its centroid, then release the puller cylinders at the lower and middle part while extend the screw jack and roller cylinders until they are 1-2 cm close to the wall. During the process of jacking, these three tie-backs will provide hori-

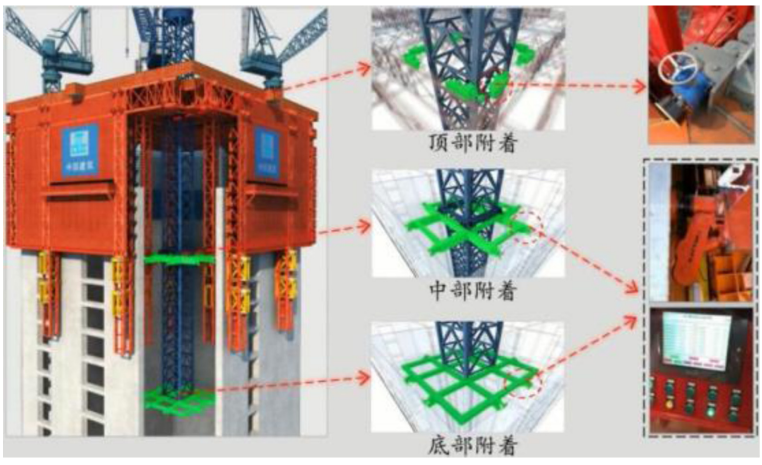


Figure 6. Integration of big tower crane.

zontal support for the tower crane in case of strong wind or bad weather.

3. Crane Slewing System

3.1. Background of the Study

The vertical transportation of components and materials for super high-rise building construction mainly rely on the tower crane. Because of the distribution of components for the typical structure system (steel frame and core tube), the defects of traditional method are obvious.

1) The large tower crane must be selected because of mega columns those located on the perimeters of the tower with only 5% of all components. At the same time, to keep a safety distance between tower cranes, multiple tower cranes cannot operate together efficiently.

2) Both in plane and vertical layouts the tower crane will interfere with other construction equipment such as formwork and hoist, which will lower efficiency in construction. The jacking, steel beam cycling and welding of tower crane also waste construction period.

3.2. Basic Introduction

To solve the above problems, absorbing the idea of the rotating table, a crane slewing system was put forward (Fig. 7). The crane slewing system integrates all the tower cranes at different levels on one platform which is able to slew around the core tube. Several obvious advantages can be gotten easily:

1) Taking advantage of the slewing function, the cover area of tower cranes is increased. Therefore, the tower cranes combination is optimized, big, middle and small tower cranes are combined together and perform most efficiently.

2) All the tower cranes will be jacked together with the slewing system. The change of structure will be easy to fit for tower cranes.



Figure 7. Crane slewing system.

3) Every tower cranes would be the backup of others to some extent.

Crane slewing system is composed by four important parts: supporting and power system, slewing driving system, steel frame and control system (Fig. 8). Supporting and power system bear the load and supply power for jacking which is similar with that of integrated platform. A slewing driving system directly holds the steel frame and supplies the power for slewing. Steel frame with the shape of "X" integrates all the tower cranes on the top of itself. A crane slewing system just like a mega-tower crane which are supported on and climb along the core-tube. The big slewing device on the top of the crane slewing system is a multifunctional X-shape arm (Fig. 9).

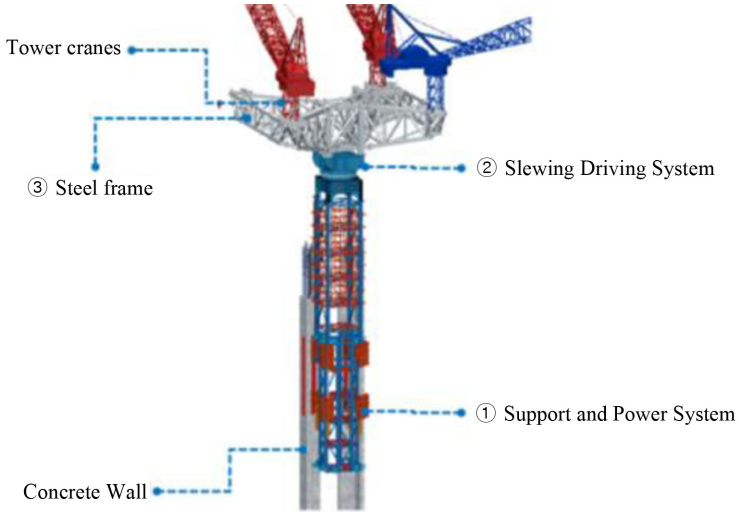


Figure 8. Composition of crane slewing system.



Figure 9. X form steel frame

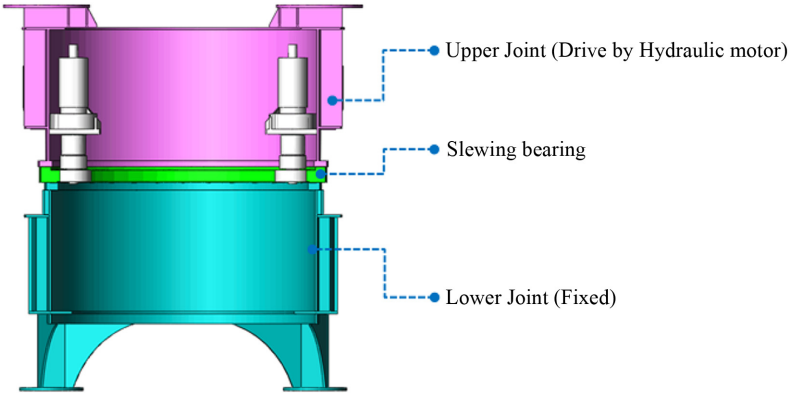


Figure 10. Composition of slewing system.



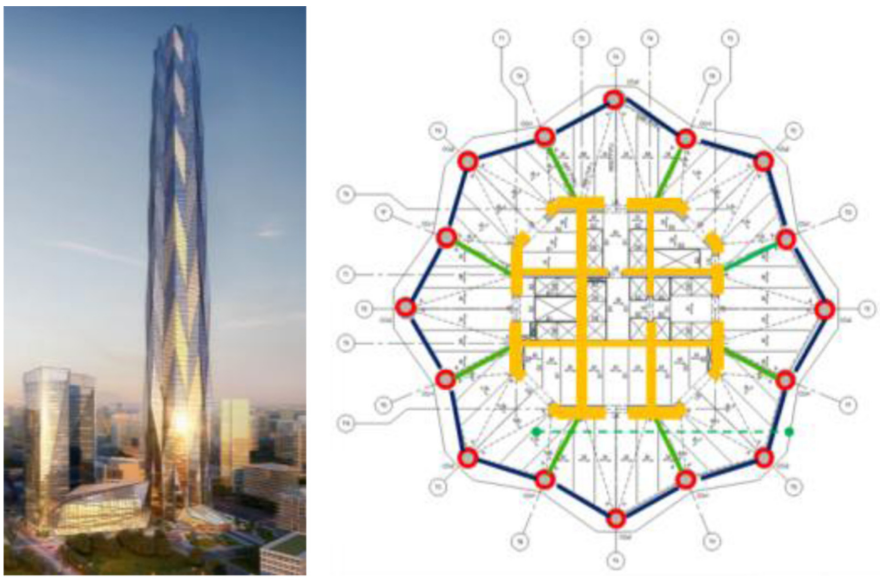
(a) Slewing bearing (b) Hydraulic motor

Figure 11. Slewing bearing and hydraulic motor.

3.3. Key Technologies

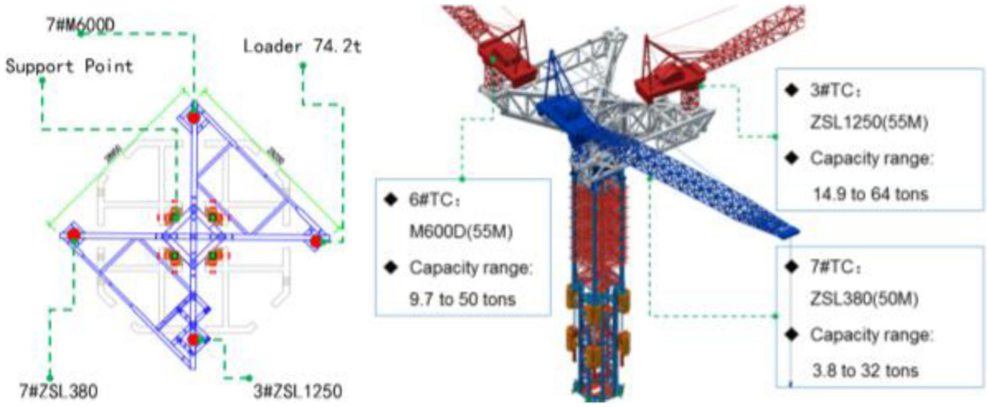
3.3.1. Slewing Driving System

The slewing driving system is composed of upper joint, slewing bearing and lower joint (Fig 10). The upper joint directly holds up the steel frame, while the slewing bearing fixed with the lower joint that connects with the upstand (Fig 11). Two hydraulic motors provides the moment for slewing. The core part is the slewing bearing which is driven by hydraulic motors. This bearing is carefully designed to take up to 2000 t axial loading, 9000 t·m turning mom-



(a) Project's Rendering (b) Typical tower plane

Figure 12. Rendering and tower plane.



(a) Plan arrangement (b) 3D model

Figure 13. Arrangement of tower cranes.

ent and 60 t radial loading.

3.3.2. Lifting Organization

Chengdu Greenland center project (468 m and 101 floor) was used to introduce the concept of lifting organization. The building has 16 composite steel columns frame and composite concrete core tube as shown in Fig 12.

Base on the analysis of construction arrangement, total lifting times is approximately 52,000 and construction peak needs three tower cranes. The lifting weights distribution are shown in Table 1.

Considering the material yards, the weight of the mega components and the total lifting times, three tower cranes were selected: 1) ZSL1250 for mega steel components lifting; 2) M600D for medium weight component lifting; 3) ZSL380 for light weight components, reinforcement and formwork. The plan and elevation arrangement of crane slewing platform and the supporting units are shown in the Fig 13.

Table 1. Lifting weights distribution

No.	Weight (t)	Percentage	Component Type
1	30-50	1%	Mega column, bracing joint, truss joint
2	10-30	5%	Mega column, bracing, truss and wall steel plate
3	<10		Other component

There are two typical working statuses. Status one: at the initial stage, ZSL1250 lifts components such as column joint and column which are at the top of the plan while M600D lifts columns at the bottom of the plan. Status Two:

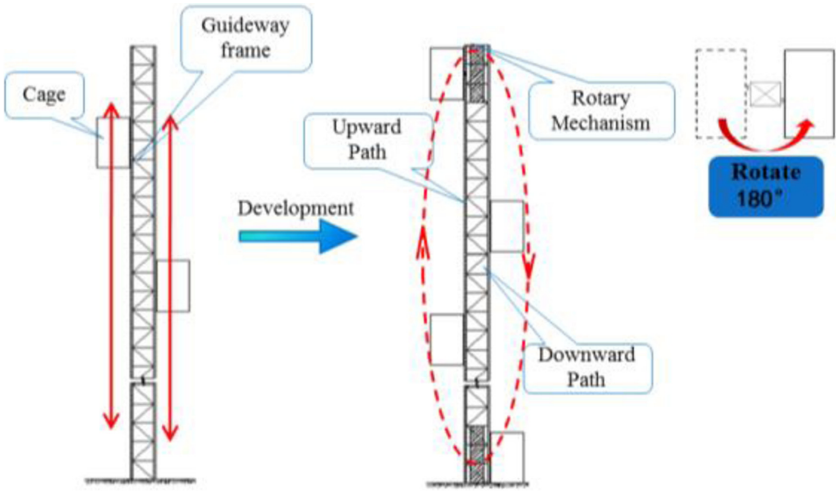


Figure 14. Principle of circular hoist.

the platform slew 180° clockwise, ZSL1250 can reach the giant joints at the bottom of the plan.

4. Circular Hoist

4.1. Background of the Study

In the construction of super high-rise building, there are usually more than ten hoists. Too many hoists occupy large operation area of different majors such as masonry and curtain wall. Some projects adopt an extra channel mast to decrease the occupation of hoists, but the cost rises accordingly. Both of these two ways will extend construction period. On the other hand, increase running speed and enlarge the dimension of the cage to increase transportation capacity are of limited effectiveness.

4.2. Basic Introduction

Accordingly, a new hoist system named as circular hoist was proposed in which multi-cages running along one single mast. The cages will run upwards on one side of the mast to certain level and slew 180 degree then go down along the other side of the mast, as shown in the following Figs. 14 and 15. It resembles a vertical subway that contains many cages running in the same circular rails.

A circular hoist consists of a rotating system, an attachment system, power supply system, monitoring and dispatching system (Fig. 16). A rotating System is the core part of the circular hoist, it helps hoist to slew at height and transfers the load to a lower mast. There are 2 types of attachment, the first one is a traditional horizontal attachment, and the other is a vertical unloading attachment; the vertical unloading attachment will transfer the load of segments between 2 vertical unloading attachments. Through sliding a bus duct, a drop in voltage and cable break is not a problem for power supply. Central control room can monitor operation status of all cages to achieve control and effective managements of all cages in time.



Figure 15. Circular hoist.

4.3. Key Technologies

4.3.1. Rotating System

Rotating system includes mechanical structure, driving and positioning system and electric control system (Fig. 17). Mechanism includes slewing frame and load bearing shaft. Slewing frame carrying hoist move around load bearing shaft while the vertical load path is exist. Slewing frame is driven by servo motor; the maximum speed is 1.5RPM. Positioning device including encoder, adjustable pinion and gear ring, the accuracy is 0.03 mm.

4.3.2. Vertical Unloading Attachments

Except of traditional horizontal attachment, the new vertical unloading attachment is used in circular hoist that including pull rod, main beam, bracing rods and Spring boxes (Fig. 18). The vertical load of segmental track between two vertical unloading attachments is transferred to these attachments directly. So the new hoist can be erected with longer a mast and more hoists. The vertical unloading

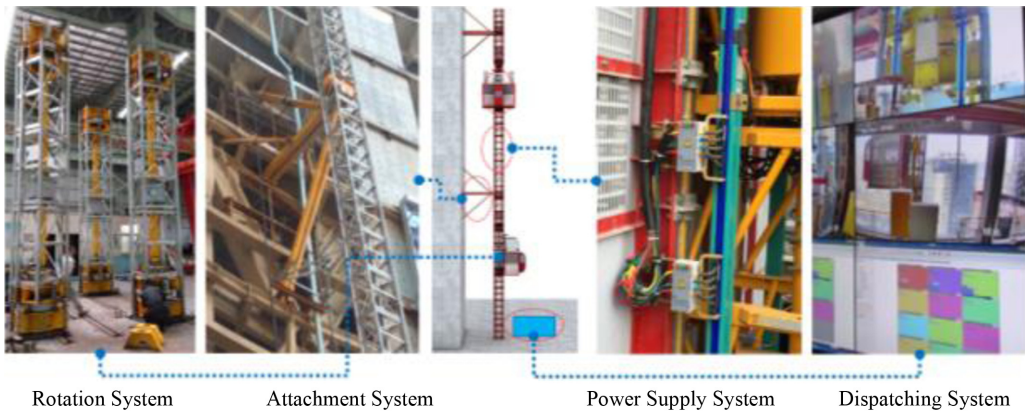


Figure 16. Composition of Circular hoist.

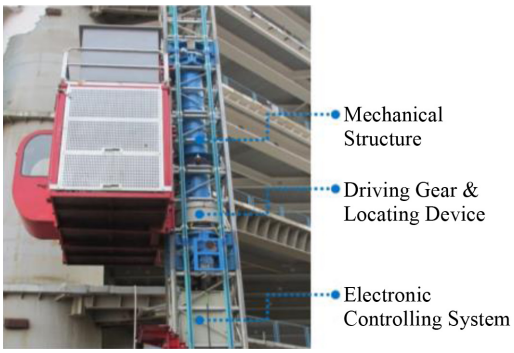


Figure 17. Rotating rail changing mechanism.

attachment can bear the load of two sections even if the upper vertical unloading attachment fail to work. Spring boxes are deployed at the bottom of vertical unloading attachment which can reduce deformation between the mast and attachment due to lighting and temperature difference. Pull rod and the main beam form a force system, while bracing rods and main beam forming another force system as the redundancy of the other.

4.3.3. Power Supply

Power supply through sliding bus duct helps a hoist slew freely (Fig. 19). A segmental power supply is adopted to resolve a drop in voltage due to multi-cages running and big height, meanwhile two sets of sliding bus duct are deployed to achieve mutual redundancy.

4.3.4. Safety of Circular Hoist

The central control is able to check the distance between the adjacent two cages. Cages will run at a high speed when the adjacent distance is not less than 40 m. Cages are allowed to run at media speed when the adjacent distance is between 40 m and 25 m. Cages are allowed to run at low speed when the adjacent distance is less than 25 m. When the adjacent distance is less than 15 m, the approaching cages will be shut down.



(a) Unloading attachment (b) Horizontal attachment

Figure 18. Unloading and horizontal attachment.



Figure 19. Sliding contact wire power supply.



Figure 20. Intelligent dispatching system.

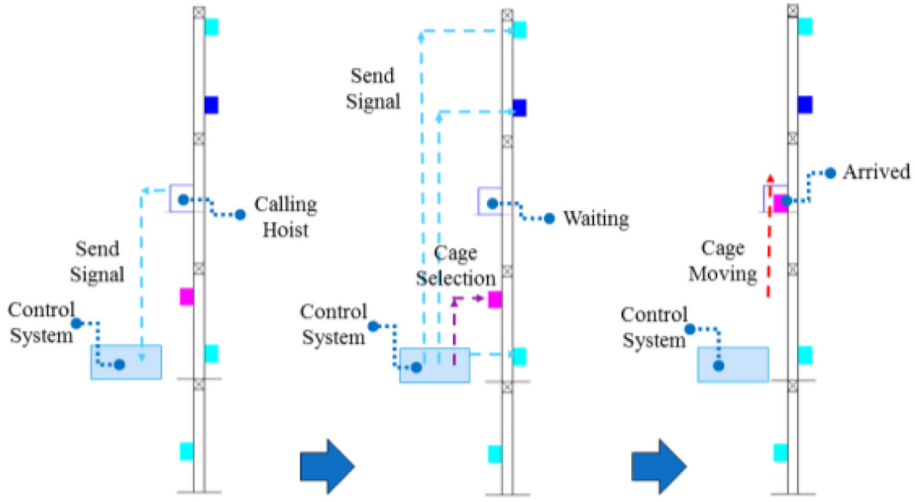


Figure 21. Hoist calling and local controls mode.

Rangefinders are installed at the top and bottom of the cages, when the adjacent distance is less than 15 m, it will automatically be alarmed and the power supply will be shut down and start braking automatically.

When cages are slewing, the cage will be locked to rotary system through vertical locking device, meanwhile power for cages will be phased out to prevent the other cages rise or descent when it is slewing. When one cage is slewing, the segments within a 9 m range will be powered off to prevent the other cage from approaching the rotation system.

4.3.5. Operation of Circular Hoist

An Intelligent Group Control Dispatching System can

dispatch all cages effectively (Fig. 20).

Hoist calling and local controls mode is the most popular way to operate the circular hoists (Fig. 21). The main processed include:

1) Request for "up", "down" and "floor numbers" can be input at the floor buttons, and the request signal will be transferred to main control.

2) The main control will follow principle of "nearest priority" and "less loading priority", and the most suitable cages will be selected and assigned accordingly, and control would send a message to the cage.

3) When a cage receives the assigned message, the operator will be informed through voice and screen, and the operator will respond accordingly to the main control system as needed.

4) When the operator accepts the assignment, the main control system will send the cage level to the applicant and the request procedure will ended. If the operator rejects the request, the main control system will calculate again until a most suitable cage is assigned.

5. Conclusion

There are still major requirements in super high-rise building for the development of construction equipment innovation, which is an important breakthrough to change the production mode of the construction industry and realize the industrial transformation and upgrading. Now, the following issues should be paid attention to:

1) The study of construction equipment should be carried out around characteristics of super high-rise building closely. These characteristics include high altitude, large scale, changeable model, various processes, complicated operation environment.

2) Both construction equipment and method (process) studies should be closely combined. Every one support the other, anyone cannot be biased.

3) A lot of construction information need to be transferred and shared rapidly for making quick decision. The high level informationization and intelligentization is the foundation to make full use of effective construction equipment.

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