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Key construction technology for complex space steel structures

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ABSTRACT

Taking the Heart of the Rainforest project in Haikou City as the research object, for the project steel structure is interlaced and complex, high precision installation requirements, tight schedule and other characteristics, from the engineering structure characteristics, processing and manufacturing, and construction methods and other aspects of the analysis: quality control measures and principles of complex space structure size, welding and assembly are proposed. At the same time, BIM technology was used to fully disassemble the structure, make a reasonable structural division, and propose a reasonable construction sequence as well as installation accuracy assurance measures, which provided a solid foundation solution for the smooth implementation of the subsequent project. The relevant results can provide technical reference for the processing and manufacturing as well as construction application of similar complex space steel structures in the future.

Keywords: complex space steel structure; BIM technology; simulation; construction key technology.

INTRODUCTION

With the development of economy and technology, the form of building structure gradually shows the development trend of complexity and versatility. Large steel structures with beautiful, novel, unique and complex spaces have come into being [1]. However, due to the uniqueness of the complex space steel structure and the complexity of the structure style, it puts forward greater requirements for the construction [2,3].The construction operation team is required to have sufficient experience, strong analytical ability and innovative construction methods to ensure the construction quality and safety of the whole structure.

Project Overview

Haikou City Rainforest Heart Project is located in the South Area of West Coast New District, Xiuying District, Haikou City. The project as a whole consists of three towers, corresponding connecting bridges as well as rain shelters. The three towers above ground all adopt steel structure system cylinder-in-cylinder structure, the outer cylinder adopts oblique intersecting quadrilateral grid structure, the inner cylinder adopts dense column frame cylinder structure; the three towers are similar in shape, all are umbrella-shaped structure, the structure is large at the top and small at the bottom, the lower part of the building is cylindrical and then gradually expands outward; the towers are connected to each other by connecting bridges, the main body of which is connected to T1 tower from the ground; the canopy is set under T2 tower. The engineering effect is shown in Figure 1.

Figure 1: Project effect

The architectural overview of the three towers is shown in Table 1 below：

Table 1: Building overview table of each tower

T1 Tower		Floor height	Elevation
Floor height and building function	1F	29.65m	Foundation top ~19.050
	2F（Viewing platform and commercial）	6.4m	19.050~ Roofing
Number of layers above the base		2F	——
Building height (m)		36.6	——
T2 Tower		Floor height	Elevation
Floor height and building function	1F	27.250m	Foundation top ~16.550
	2F	5.950m	16.550~22.500
	3F（Viewing platform and commercial）	4.900	22.500~ Roofing

Number of layers above the base		2F	——
Building height (m)		38.100	——
T3 Tower		Floor height	Elevation
Floor height and building function	1F	31.600m	Foundation top ~21.000
	2F（Bathroom and outdoor viewing platform）	5.3m	21.000~26.300
	3F（Viewing platform and commercial）	6.4m	26.300~ Roofing
Number of layers above the base		2F	——
Building height (m)		43.800	——

Technical difficulties of structural construction

- **Structural characteristics of the project**

The structure of this project has the following characteristics：

T1, T2 and T3 towers weigh 655.61t, 613.02t and 783.28t respectively. three towers are divided into inner and outer cylinders, the inner cylinder is vertical structure, the outer cylinder is umbrella structure, the two cylinders are connected and fixed by steel beams; among them, the inner cylinder is composed of 6 box columns, the steel column specification is ¨300*300*14, a rotating staircase is set along the outer side of the inner cylinder from the structure ±0.00m to the roof; the outer cylinder is composed of diagonal box columns, the steel column specification is ¨150*600, the thickness is 18mm, 25mm and 28mm. The outer cylinder is composed of oblique intersecting box-type steel columns with specifications of ¨150*600 and thicknesses of 18mm, 25mm and 28mm. all structural materials are Q355.

The total weight of the connecting bridge is 496.80t, which consists of three parts: the connecting bridge between T1 tower and T2 tower, the connecting bridge between T2 tower and T3 tower and the connecting bridge between T1 tower and ground; the connecting bridge between towers is mainly fixed by supporting round tubes set on the towers, the connecting bridge from T1 tower to ground is fixed by the combination of steel ties and pins with three towers in the space intersection area. The remaining area is fixed in the form of V-shaped columns. The whole bridge is a steel frame structure, the main cross-section is made of steel round pipe, steel moment pipe and H-beam; the width of the bridge deck is 3m, the total length is about 320m, and the grating is laid on it.

The total weight of the canopy is 531.9t, at the bottom of T2 tower, length 122m, mesh shell structure, overall style similar to DNA, the main material section is box section.

The schematic diagram of the project structure is shown in Figure 2.

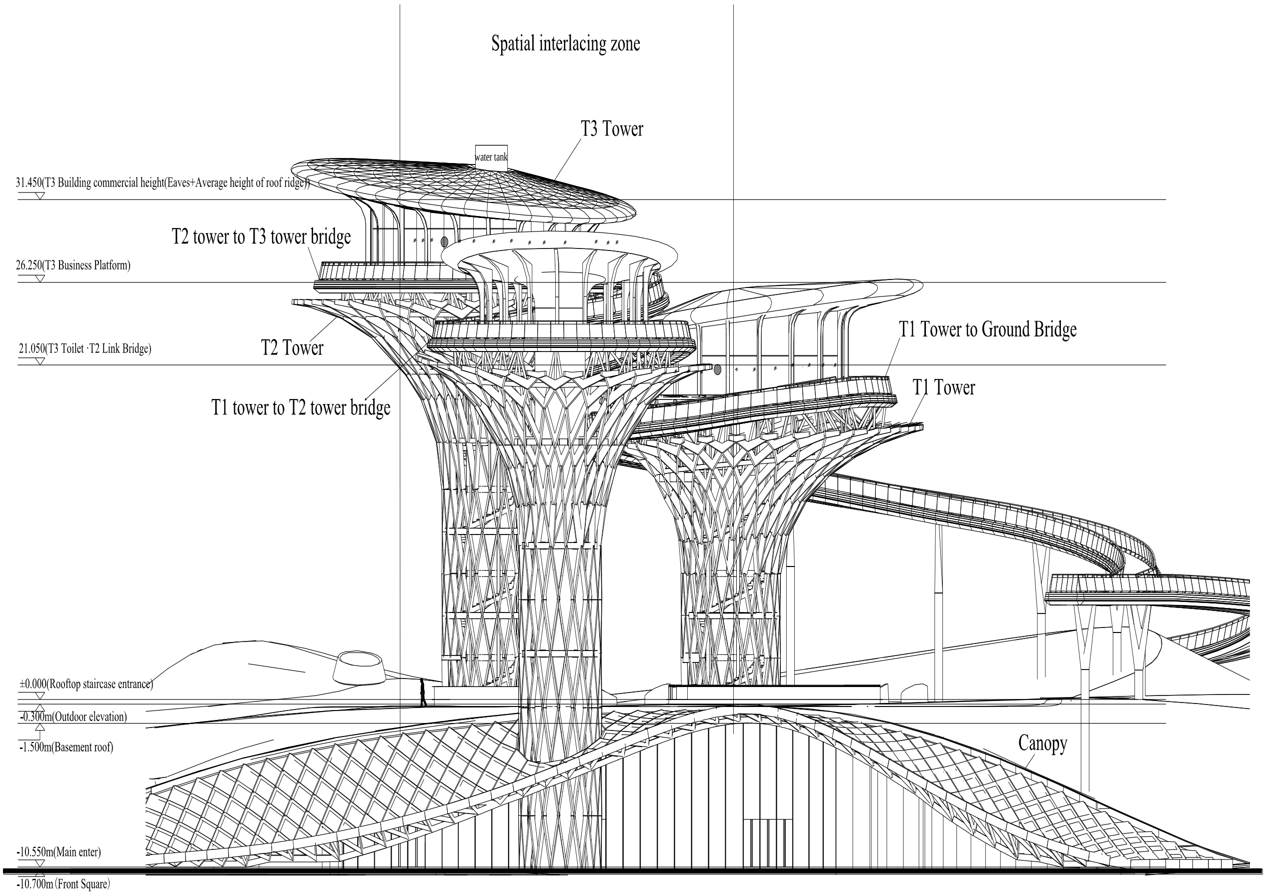


Figure 2: Schematic diagram of the project structure

- **Analysis of construction priorities and difficulties**

(1) The project is basically a spatial torsion bar, and the deepening design of the torsion bar (curve positioning, model establishment, etc.), the accuracy control of the processing process and the segmentation of the structure are important links and difficult points to consider before the implementation of the whole project.

(2) The project structure space intersection area (mainly exists between the three towers and the connecting bridge) has up to 4 layers of structure in the vertical direction of projection overlap (as shown in Figure 3), so the construction sequence must be reasonably arranged, and detailed safety and installation accuracy assurance measures must be formulated to ensure the construction period and quality.

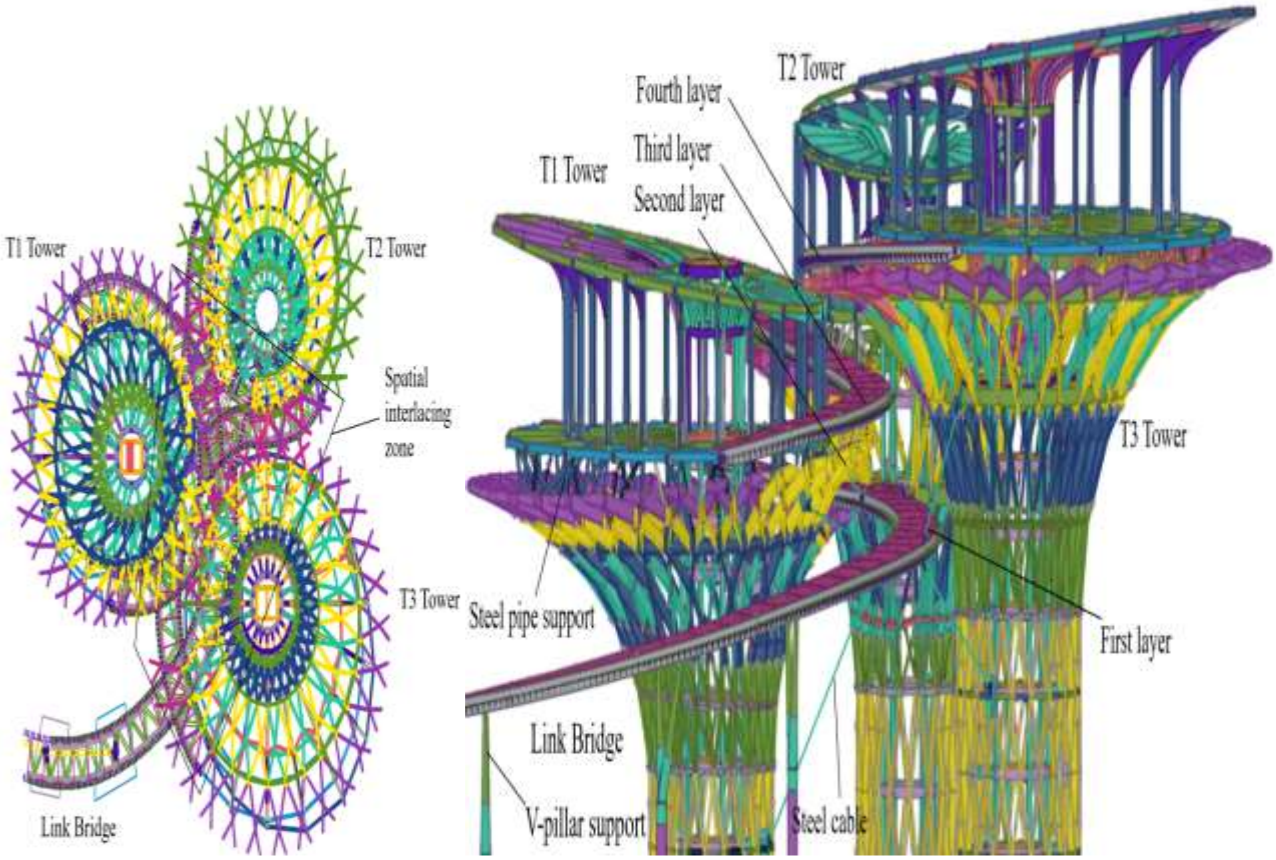


Figure 3: Structure space relationship

Structural processing quality control

- **Processing Processes**

Complex space structure processing and manufacturing must be clear before the entire structure of the processing process, in order to facilitate the subsequent process inspection, timely grasp of the processing dynamics. The processing process flow is shown in Figure 4 below:

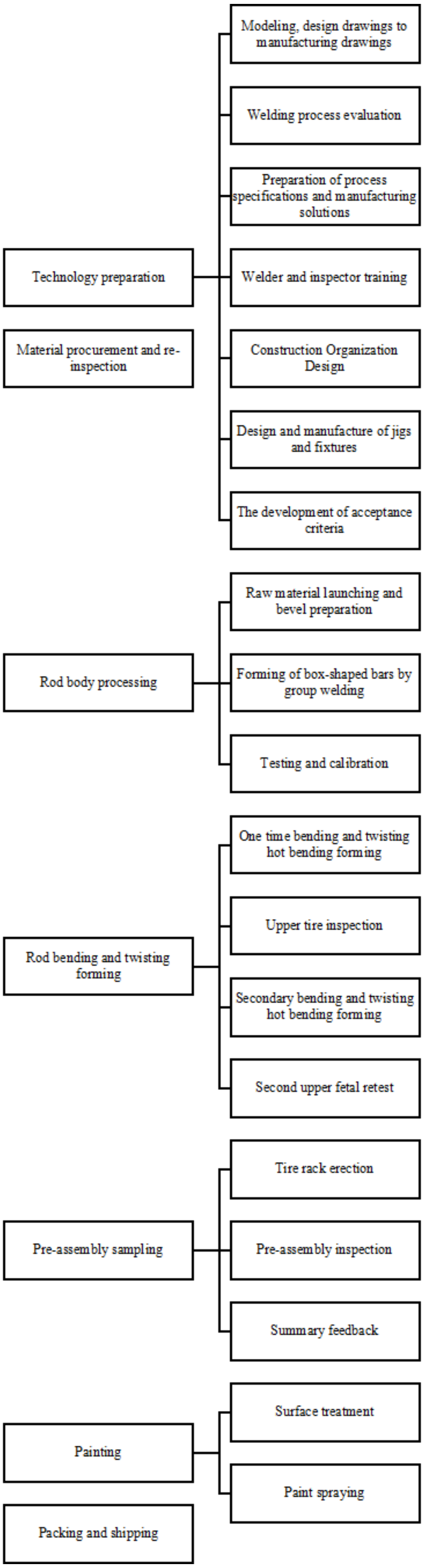

Modeling, design drawings to manufacturing drawings
Welding process evaluation
Preparation of process specifications and manufacturing solutions
Technology preparation
Welder and inspector training
Material procurement and re-inspection
Construction Organization Design
Design and manufacture of jigs and fixtures
The development of acceptance criteria
Raw material launching and bevel preparation
Rod body processing
Forming of box-shaped bars by group welding
Testing and calibration
One time bending and twisting hot bending forming
Upper tire inspection
Rod bending and twisting forming
Secondary bending and twisting hot bending forming
Second upper fetal retest
Tire rack erection
Pre-assembly sampling
Pre-assembly inspection
Summary feedback
Surface treatment
Painting
Paint spraying
Packing and shipping

Figure 4: Processing process flow

- **Control measures for dimensional errors of components**

In order to ensure the quality of on-site assembly and installation as well as the smooth progress of lifting work. The control of component size error is an important guarantee link [4], and its main measures are as follows.

1）Split and block division

Due to the large size of the bending and twisting members, and most of the nodes are welded connection nodes, in order to ensure the precision of the production of the factory components, especially the processing quality of the interface, before the large area processing of the components, all the structures need to be divided into pieces and blocks.

2）Setting and requirements of assembled tire frame

The tire frame should be drawn out the bottom line according to the sketch, and the node line, center line, segment position line and enterprise mouth line of the preassembled members should be drawn out on the ground, and welded firmly with small iron plate, and knocked on the foreign punch.

According to the projection line of the center of each member, vertical support is set at about 600 mm from the docking point of each member. The elevation of the tire frame support should be placed according to the actual shape of the structure. The tire frame shall not have obvious shaking, and must be fixed with diagonal bracing.

The allowable deviation of the important dimensions of the tire frame assembly is shown in Table 2 below.

Table 2: Tire frame assembling important size allowable deviation

Projects	Allowable Deviation（mm）
Node axis line error	$0 \leq \delta \leq 1$
Docking elevation	±1.5
Levelness	±1

3）Assembling requirements

Before assembling, a unit needs to be picked for pre-assembly to check the production accuracy and repair process measures.

The correctness of the interface needs to be checked when assembling, and the alignment mark line needs to be scribed at the interface position at the site assembling, as the baseline of the component transported to the site assembling. Welding requires the use of small line energy welding process specification, in order to reduce the deformation of the components welding. Canopy structure factory pre-assembly as shown in Figure 5.

Figure 5: Canopy structure factory pre-assembly

- **Welding quality control measures**

➢ **Welding process evaluation test**

Due to the novel structure, the welding process evaluation test must be done before welding in order to ensure the welding quality. The main relevant parameters are shown in Table 3 below:

Table 3: Main process evaluation parameters

Material	Manual welding rod type	CO_2 Gas shielded welding solid core wire type	Submerged arc welding materials (flux + wire)	Preheating temperature	Interlayer temperature
Q355	E5015	ER50-2	F5024+H10MN2	Thickness <25mm, no preheating. Thickness≥25mm, preheat 60-150℃	200-230℃

➢ **Control of interlayer temperature in the welding process**

When welding thick plates, the cooling rate of the plate temperature is faster, causing the temperature to drop. In order to make the interlayer temperature of welding has been maintained between 200-230 ℃, in addition to the use of digital automatic temperature control box to adjust the infrared heating plate heating temperature, while using digital thermometer, at any time the front and rear direction of the welding point, side temperature measurement. It must be noted that the preheating temperature and interlayer temperature must be checked before each welding channel is about to arc welding.

➢ **Control of welding deformation**

The production of thick plate structure, in addition to the prevention and avoid laminar tearing, must also pay attention to avoid the deformation of the thick plate structure, such as deformation, the difficulty of correction is very large (if it is a box-shaped components, there is a distortion deformation components can only be scrapped); at the same time, the accuracy of the shape of the components can not be guaranteed, resulting in the site can not be installed;Therefore, for the thick plate structure welding melt volume, deep welding channel, especially the box-shaped structure of super-thick plate, small cross-section, large bevel, welding stress concentration and more prone to deformation, the following control methods and measures are adopted：

(1) Making the welding horizontal station tire frame for assembly;

(2) set the anti-deformation, pre-release welding shrinkage deformation margin;

(3) the choice of reasonable bevel form, reduce the amount of fusion filling;

(4) set the tire fixture to restrain deformation;

(5) to adopt a reasonable welding sequence.

Construction key technology analysis

- **BIM technology application**

Tekla Structures software plays a vital role in the deepening design and construction of steel structures [5,6,7]. The model is generated by inputting parameters into the software based on the design drawing information. Through the model, the spatial interrelationship between the structures, the blocking method, the structural dimensions, the weight and the center of gravity and other parameters can be intuitively grasped, as shown in Figure 6:

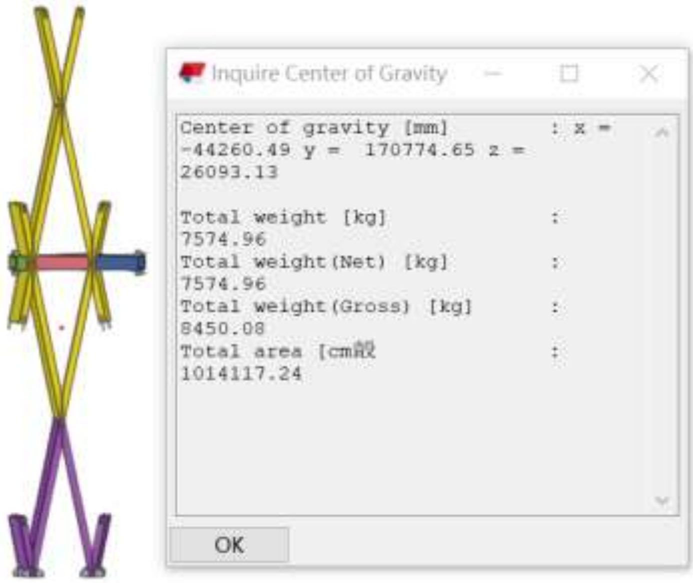
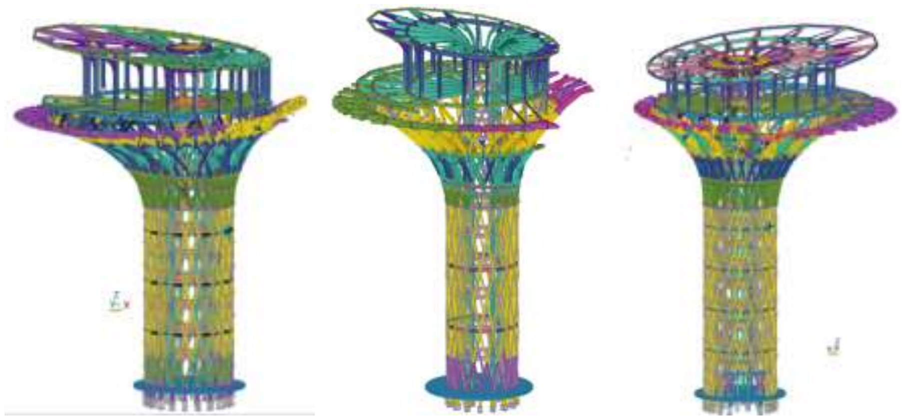


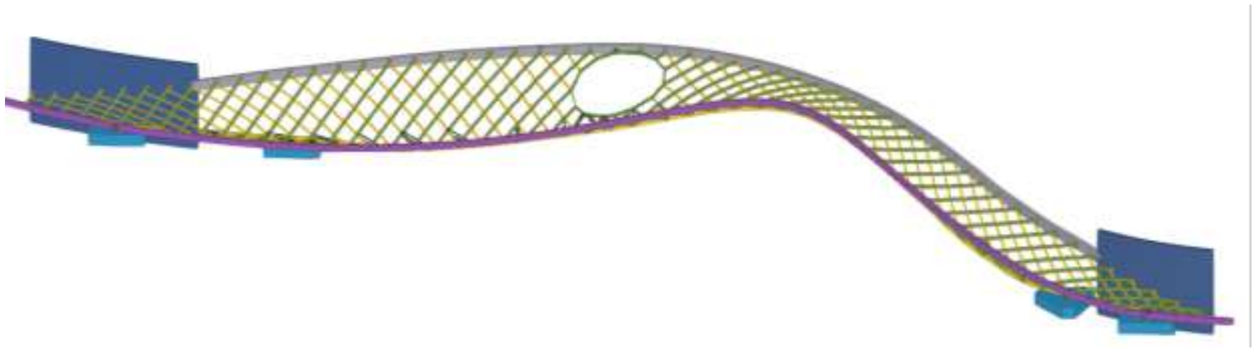
Figure 6: Structure information parameters

When deepening the modeling, the basic principle of this project is: according to the deepening idea of sub-layer and sub-elevation, first single body and then detail, first whole and then block. The completed model is shown in Figure 7：



(a) T1 Tower Structure (b) T2 Tower Structure (c) T3 Tower Structure

(d) Connecting bridge structure



(e) Canopy structure

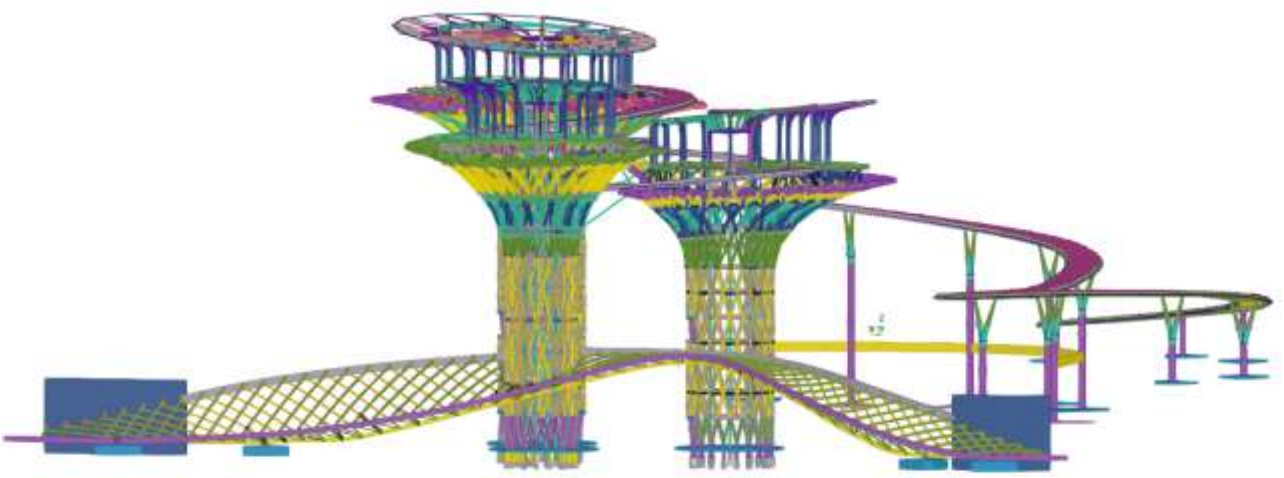


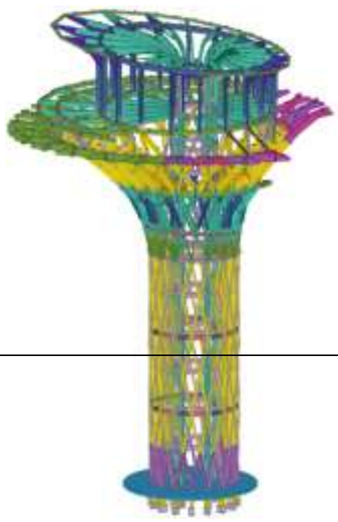
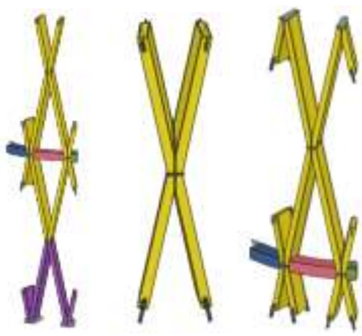
Figure 7: Deepening model effect

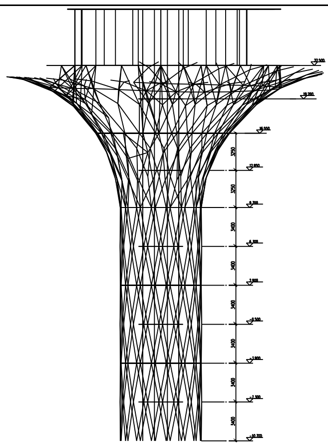
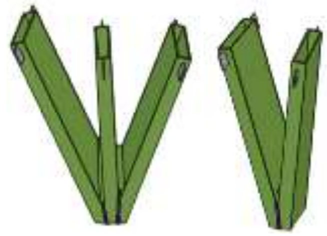
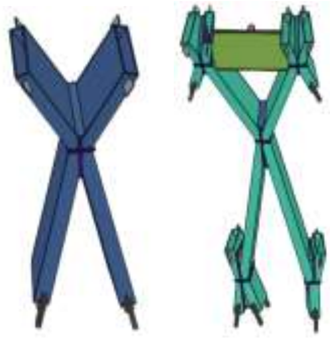
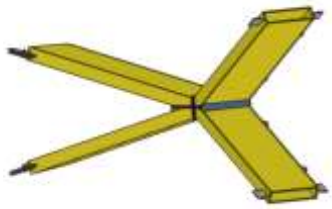
- **Structure division**

Due to the complex nature of the structure, in order to improve construction efficiency and ensure quality faster, it is necessary to divide the structure into blocks by considering many aspects such as structural characteristics, processing, transportation, on-site lifting environment and measure costs.

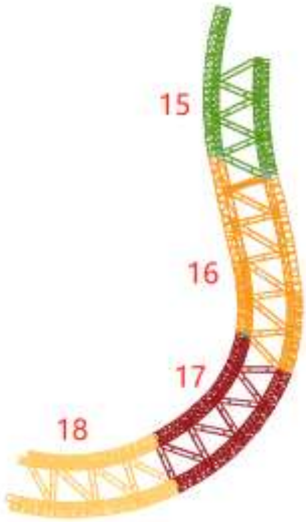
When dividing, the block is divided into the largest as possible under the condition that the site lifting situation allows and the deformation of the components is small. When dividing the tower, the main consideration is the division of the outer steel structure, and the rest of the components can be divided according to the layer elevation or connection nodes, taking the T2 tower as an example, the main structural division is shown in Table 3：

Table 3: T2 tower main structure division table

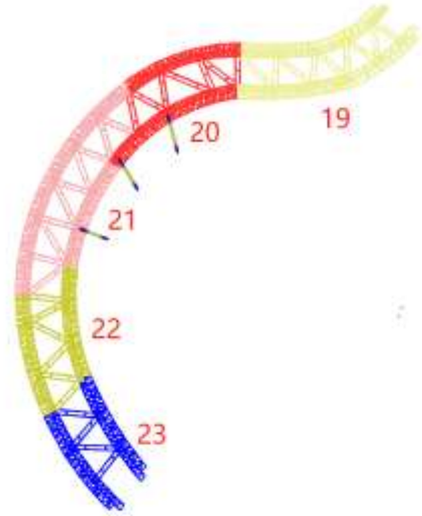
Structure	Figure legend	Elevation	Structure division
T2 Tower		-10.7m ~9.7m	

		9.7m~12.95m	
		12..95m~16.55	
		16.55m~19.2m	
		19.2m~22.5m	

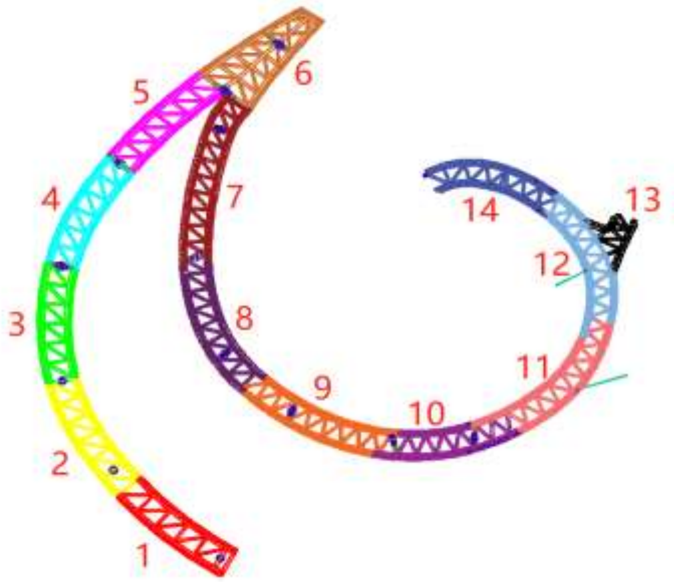
The division of the connecting bridge with the main break set in the location of the pier support and temporary support frame, the total plan is divided into 23 sections, as shown in Figure 8 ：



a）Connecting bridge between Tower 1 & Tower 2



b）Connecting bridge betweenTower2&3



（c）Connecting bridge from Tower 1 to ground level

Figure 8: Division of connecting bridge structure

The division of the canopy structure can be divided into strips according to one direction, and the remaining ones are assembled as loose parts, and the division style is shown in Figure 9：

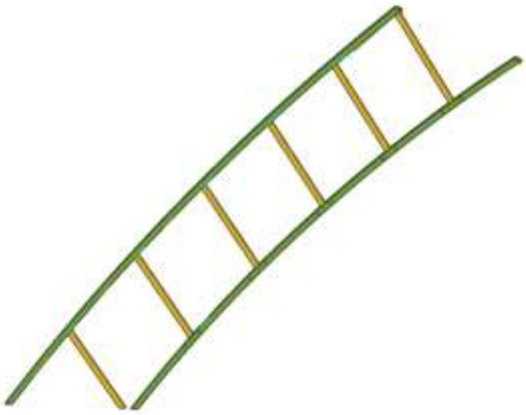
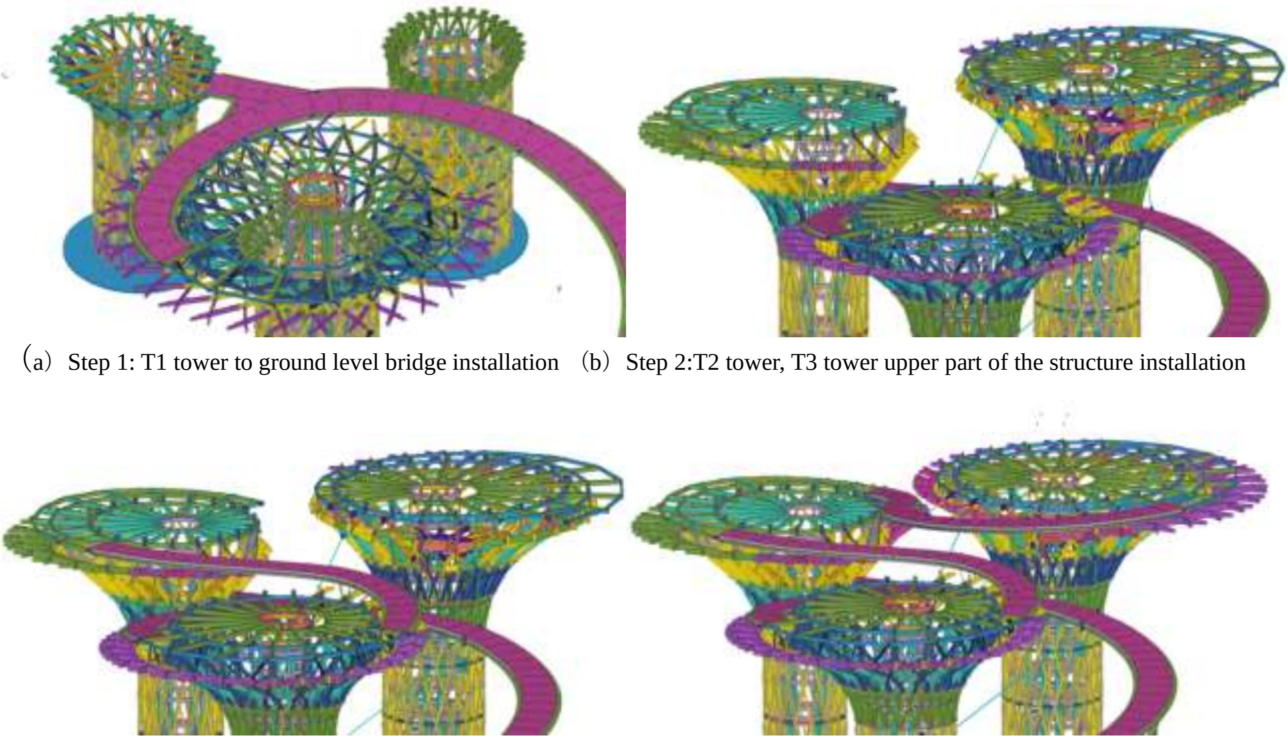


Figure 9: Canopy structure division style

- **Main construction methods**

➢ **Construction sequence arrangement**

The construction sequence of the whole project needs to be focused on the construction and installation of the structure in the interlocking space. That is, the corresponding installation sequence between the connecting bridge and the three towers needs to be clarified. The main principle is: the priority is to meet the lifting of the connecting bridge, and the connecting bridge is installed in order from the bottom to the top. The key installation steps are shown in Figure 10 below：



（a）Step 1: T1 tower to ground level bridge installation （b）Step 2:T2 tower, T3 tower upper part of the structure installation

（c）Step 3: T1 tower to T2 tower connecting bridge installation （d）Step 4: T2 tower to T3 tower connecting bridge installation

Figure 10: Key Installation Steps for Spatial Intersection Zone

➢ **Important measures and methods**

(1) Installation measures for the outer barrel outer sloping quadrilateral grid structure

The quadrilateral grid structure with oblique intersection of outer cylinders above 5.3m for T1 tower, 9.7m for T2 tower and 13.25m for T3 tower is installed with external center of gravity, as shown in Figure 11. If no measures are taken during installation, structural instability or excessive structural deformation will easily occur, so in order to ensure construction efficiency, safety and installation quality, and on the premise of minimizing the cost of measures; a round steel of φ30 is used to temporarily connect the members (the heaviest is 5.5t) with the middle inner cylinder to fix them, as shown in Figure 12:

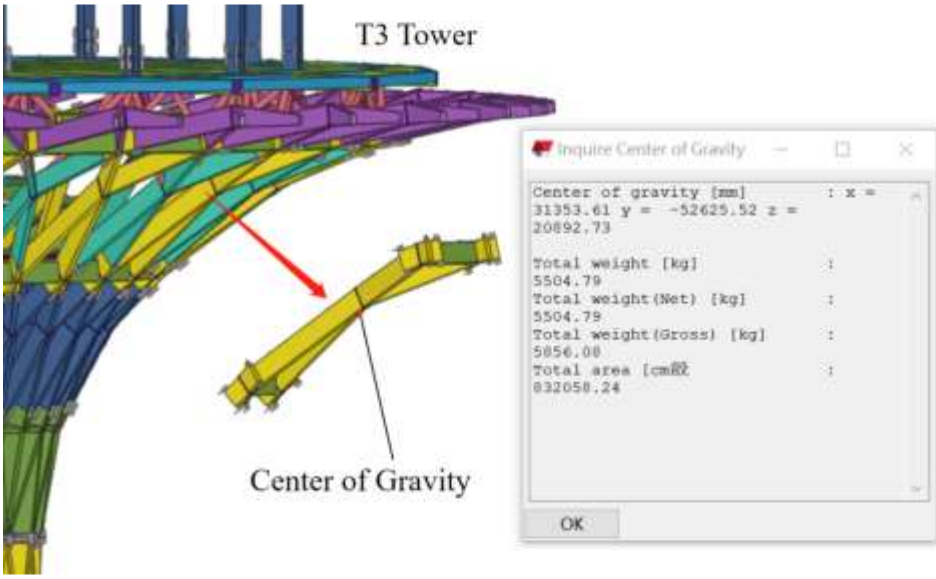


Figure 11: Schematic diagram of the center of gravity of the structure

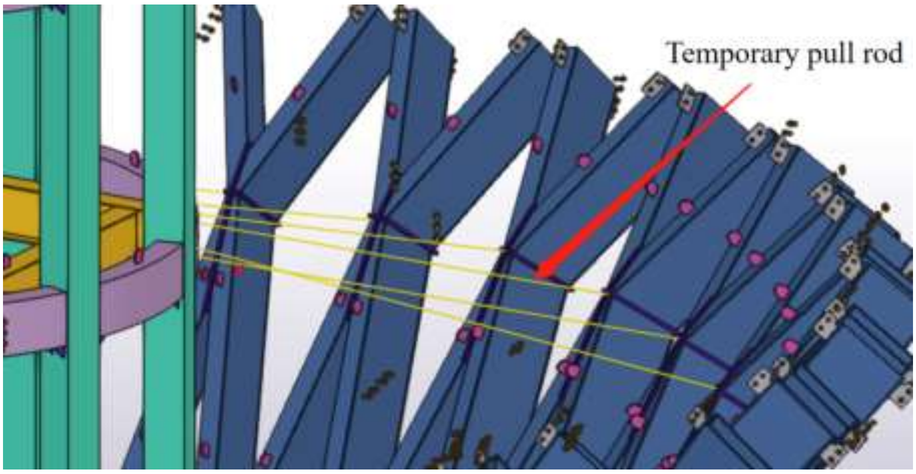


Figure 12: Temporary tie bar setup

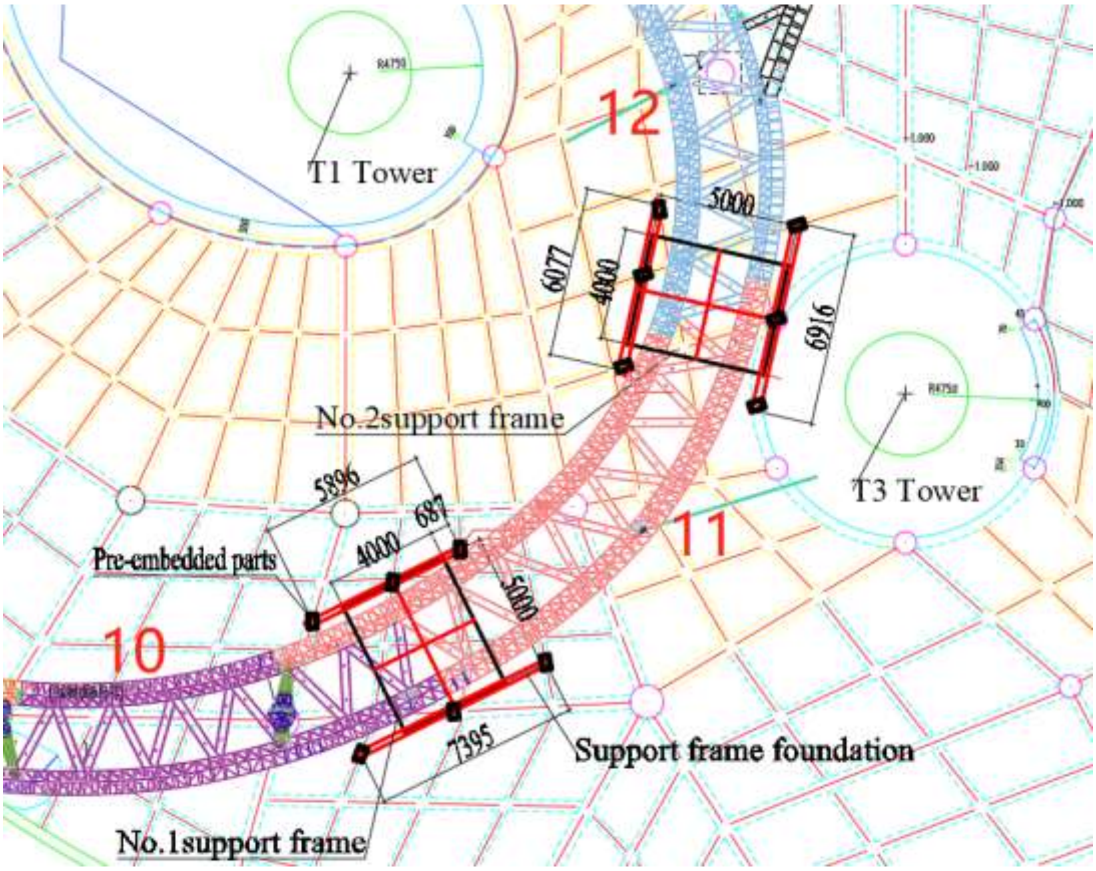
(2) Even the bridge installation measures

Since the connecting bridges between the three towers are basically located on the structure of the towers, there is no need to consider separate support measures for the installation. According to the segmentation and construction sequence study, when installing 11 and 12 sections of the connecting bridge, the corresponding steel ties cannot be installed and fixed, so it is necessary to set up support frames at the interface of the three sections of the connecting bridge to meet the installation requirements. Therefore, two 5m*4m support frames were erected at the interface, and a conversion beam was set under the support frame for converting the reaction force of the support frame column to the concrete beam, and the relevant parameters of the support frame are shown in Table 4 below：

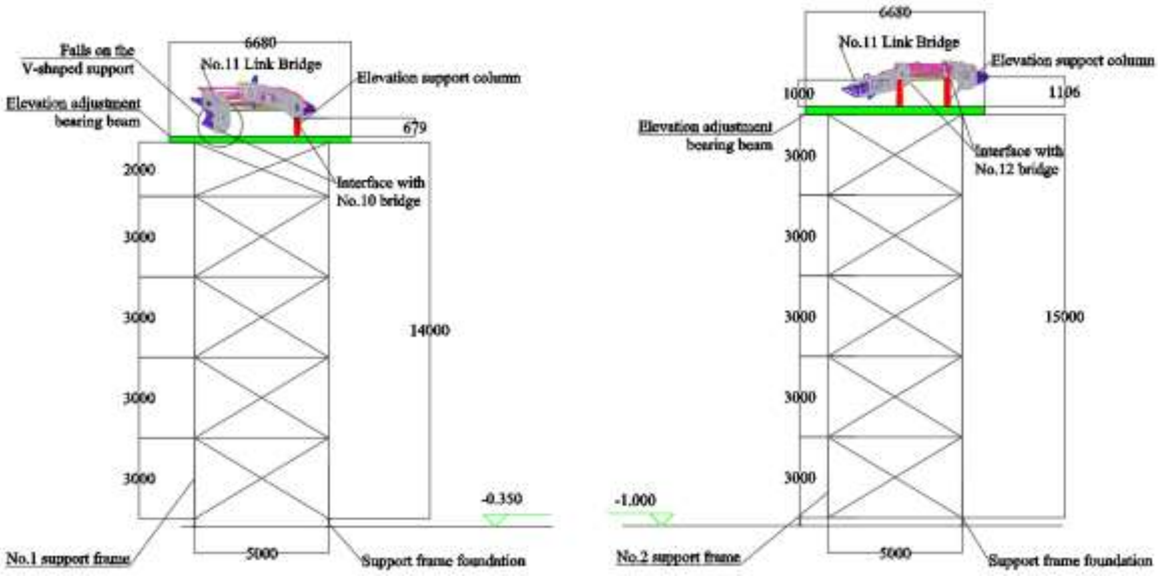
Table 4: Support frame related parameters

Support frame number	Racking height	Shelf/elevation adjustment column section type	Cross-sectional type of transfer beam/elevation-adjustable load bearing beam
No. 1	14m	φ203*10	H300*220*6*8
No.2	15m		

The relevant practices and locations of the support frame erection are shown in Figure 13 below：



(a) Support frame plan layout



（b） Support frame practice diagram

Figure 13: Support frame erection related practices, location

- **Installation accuracy control measures**

When the members are installed in sections, the axis and elevation correction is carried out by two total stations. Before lifting, a measurement control point is set at the end of each section and the three-dimensional design value of this point is calculated, and the coordinates of the long side or diagonal point of the box beam of the section control point are used as the control point of the installation space position [8]. When measuring, two total stations are placed on the orthogonal axis control line, and after accurate alignment and leveling, the alignment is fixed, and then the telescope is turned longitudinally to align the marking points on the end and take readings, and after comparing with the design control value, the correction direction is judged and the hoisting personnel are directed to correct the members until both orthogonal directions are corrected to the correct position. The error between the actual point value of installation and the design control value is controlled at ±10mm.

CONCLUSION

The unique structural design of the Heart of the Rainforest project in Haikou City, with its unique appearance and its complex spatial structure shape brought great challenges to the construction, and the following conclusions were drawn through analysis.

1.For the structural characteristics, the relevant processing process and processing quality control methods are proposed, which effectively guarantee the processing quality of the components and the accuracy of the subsequent on-site installation.

2.The full use of BIM technology, intuitive and effective detailed analysis of the structure, advance prediction of possible problems in construction, clearly grasp the details of the structure of the difficult points, conducive to management and technical personnel to better guide the site construction.

3.For the complex space structure, it is necessary to analyze it as a whole and develop a feasible construction plan by combining the force characteristics of the structure and the installation environment in order to most effectively improve the construction progress, save money and ensure the quality of the project.

4.The construction method and technology used in this project can effectively guarantee the safety of the project and make the construction quality controllable. It has certain reference value for the space steel structure project with complex structure.

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