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Design study on the improvement of dynamic characteristics of wind-resistant performance of large-span steel structures using the finite element method

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Abstract Large-span steel structure is widely used in modern buildings because of its advantages such as light weight and high strength, but its large span and small damping characteristics make it prone to excessive deformation and dynamic response under wind load. This paper takes a large-span steel truss structure of a stage play as an example, analyzes the dynamic characteristics of the wind-resistant performance of the large-span steel structure by using the finite element method and puts forward an improved design scheme. The study adopts 3D3S and ANSYS software to establish a finite element model of the steel structure, and analyzes the static and dynamic responses of the structure in different wind directions and wind speeds, and explores the effects of wind loads on the structural displacements, static three-dimensional forces and stability. The results show that: when the wind speed reaches the critical value of 170m/s, the transverse displacement in the span of the main girder increases from 41.22mm to 66092.45m, presenting the phenomenon of displacement dispersion, and the structure is destabilized and damaged; the structural instability pattern varies in different wind angles of attack, with a combination of spatial bending and torsion in the angle of attack of 0°, and mainly transverse bending instability in the angle of attack of ±5°; and the results of the component load bearing capacity calculation show that The results of load capacity checking show that all the main steel members of this project meet the performance target of not yielding under the action of 16.5 grade typhoon. Based on the analysis results, the study proposes the improved design scheme of using triangular tube truss columns and beams to form a spatial portal transverse bearing whole, and optimizes the key construction technology, which effectively improves the wind resistance performance of the structure and provides theoretical basis and technical support for the wind resistance design of large-span steel structures.

Index Terms Long-span steel structure, Wind resistance, Finite element method, Dynamic characteristics, Static wind instability, Improved design

I. Introduction

Taking the opportunity of the 2008 Beijing Olympic Games and the 2010 Shanghai World Expo, a wave of construction of large-span stadiums (stadiums) has been set off in China, with the emergence of such large-span, innovative and complex buildings as the “Bird's Nest” and the “Water Cube”. The building materials, structural system and design have become more and more popular. With the continuous innovation of building materials, structural systems and design and construction technology, the height and span of buildings are also breaking new records, the structural system is constantly developing towards flexibility, and the wind-resistant design of structures has become an important aspect of structural design [1]-[3].

Without wind, the design of structures, especially large structures, would be much easier and less expensive. These large-span structures are subject to complex forces, less damping, and are in a low atmospheric boundary layer with high turbulence, where the wind-driven dynamic response is more pronounced, and very often it is no longer possible to design them purely on the basis of codes, and in particular, the wind-resistant design of these structures is almost unsupported [4]-[7]. The wind resistance research of building structures is a systematic project, in the wind resistance research of large-span structures, the main task of engineering researchers is to summarize the law of wind pressure distribution on the surface of the structure from the building forms with very different shapes, to explain the mechanism of wind pressure distribution, and to obtain the equivalent static wind load through the analysis of the wind response of the structure [8]-[10]. However, due to the increasingly high demand for beautiful building shapes, the wind resistance of its structure is good with the beautiful form of modeling, and often can not be unified. The bottleneck encountered in the study of wind loads on large-span building structures is that, on the one hand, structural engineers need to have a comprehensive understanding of the loads and wind effects of the building during design to obtain the optimal combination of building form and building cost, and on the other hand, the ever-changing form parameters when optimizing the building scheme bring great uncertainty to the wind loads of the structure [11], [12]. In the traditional wind-resistant design, the node design accuracy is missing while the pulsating wind pressure is simplified by static equivalence, but under the actual wind force, especially in typhoon weather, the aerodynamic damping contribution is neglected and obtaining the non-Gaussian characteristics of typhoon is hindered [13]-[17]. It highlights the urgency of improving the wind-resistant design of large-span steel structures.

The finite element method (FEM) is a modern computational method rapidly developed for structural mechanical analysis. It is an effective numerical analysis method firstly applied in the static and dynamic characterization of aircraft structures in the field of continuum mechanics in the 1950's, and then it was soon widely applied in solving continuum problems such as heat conduction, electromagnetic field, fluid dynamics, etc., and it has the advantage of the improvement of the dynamic characteristics of the large-span structures [18]-[20].

Large-span steel structures are widely used in modern buildings due to their advantages of light deadweight, high strength and short construction period. However, large-span steel structures usually have large aspect ratios and small structural damping, and are prone to excessive deformation and dynamic response under wind loads, which brings serious challenges to the safety of the structures. In recent years, extreme weather events such as typhoons have occurred frequently in China, and a number of wind accidents of large-span steel structures have shown that insufficient wind resistance of the structure has become an important factor restricting its safe operation. There is a significant difference between the force performance of long-span steel structures in the construction phase and the use phase, and the traditional design method usually focuses on the use phase of the structure, while the wind resistance performance during the construction process is not sufficiently concerned. Since the structural system has not been fully formed during the construction stage, its overall stiffness and stability are lower and more likely to be adversely affected by wind loads. It is of great significance to analyze the wind resistance performance of large-span steel structures in the whole process of dynamic characterization to ensure the safety of the structure in the whole life cycle. At present, numerical simulation based on the finite element method has become an effective means to study the wind resistance of long-span structures, which can not only simulate the various working conditions of the structure under the ideal inflow conditions, but also analyze the distribution characteristics of the flow field in the area near the inflow through the structure in a figurative way, which provides a powerful support for the design of the structure to resist wind. Scholars at home and abroad have conducted a large number of studies on the wind resistance of long-span structures, but most of the studies focus on the wind pressure distribution and wind vibration response of the structure, and there are relatively few studies on the dynamic characteristics of the wind resistance of structures and their improved design, especially for the lack of research in the construction stage. In addition, the traditional wind-resistant design is mainly based on the standard wind load value given in the specification for static checking, which is difficult to comprehensively reflect the real dynamic response characteristics of the structure under the action of wind load.

In this study, a large-span steel truss structure for load-bearing of a stage play is taken as the engineering background, and the dynamic characteristics of its wind-resistant performance are analyzed by using the finite element method, and the corresponding improved design scheme is proposed. The study firstly establishes CAD model by 3D3S software, and then imports ANSYS finite element software to carry out mechanical analysis; secondly, the structure is subjected to load capacity calculation and limit state analysis to evaluate its force performance under different wind load combinations; then, the whole process of static wind instability analysis and the impact analysis of different wind angle of attack are carried out to investigate the mechanism of the structural instability and the critical wind speed; lastly, based on the results of the analysis, it is proposed that a new design method is adopted to improve the dynamic characteristics of wind resistance. Finally, based on the analysis results, the structural improvement design scheme with space tube truss as the core is proposed, and the construction key technology is optimized. By combining theoretical analysis and engineering practice, this study not only reveals the dynamic characteristics of wind-resistant performance of long-span steel structures, but also provides useful references for the wind-resistant design and construction of similar projects, which is of practical application value to promote the design of wind-resistant performance of long-span steel structures.

II. Design Study on Wind Resistance Improvement of Large-Span Steel Structures

II. A. Projects

II. A. 1) Overview of the project

The monitoring project is a large-span steel truss structure, which is used as the load-bearing structure for the choreography, lighting, sound and props of a stage play. The project is a main steel planar truss structure system with a length of about 131 meters, a maximum span of about 81 meters, and the highest point of the structure is 29.333 meters in elevation, in which the support is located on the top of the concrete grandstand columns with an elevation of about 1 meter to 30 meters. The steel truss main structure consists of 18-bay planar main trusses, lateral secondary trusses, steel tie rod supports and secondary beams for equipment hanging, with the bottom of the truss columns hinged to the lower concrete structure. Except for the secondary beams which are H-beam and steel tie rods for support, all other rods are made of round steel tubes. The main and secondary trusses are connected with each other by coherent nodes or flanges, and hollow welded ball nodes are adopted for some nodes with large internal force. The supports are pin and seismic ball-hinge support nodes. The main large-span steel truss structure is designed by an architectural design institute. Compared with the Q235B material, the material used for the steel truss is Q345B steel structure and steel ties, and Table 1 shows the mechanical property parameters of the materials.

The mechanical parameters of the steel structure materials used in this project are as follows.

(1) Steel material. All the main steel structure materials are made of Q345B grade steel, the quality of which is in accordance with the specification of “Low Alloy High Strength Structural Steel”. The ratio of yield strength to measured tensile strength of steel should not be greater than 0.842, with obvious yield step and elongation greater than 19.52%. The steel should have good weldability and qualified impact toughness. All steel are welded structural steel, should be in accordance with the standards required by the specification for tensile testing, bending test, V-notch impact test, Z performance and melting analysis, should also meet the requirements of weldability.

(2) Steel tie rods. Tie rods used in this project for UU-type steel tie rods, strength class 500, yield strength ReH ≥ 500MPa, tensile strength Rm ≥ 700MPa, elongation A ≥ 18.72%, section shrinkage Z ≥ 49.53%, impact work (longitudinal) Akv ≥ 33.84J (-18.27 ℃) the theoretical yield load is not less than 144 kN. unannotated technical requirements in accordance with “the Steel Tie Rod” GB/T20934-2007 regulations.

(3) Connection materials.

(a) Welding rod, flux and wire.

For Q235 grade steel with E43 series welding material, for Q345 steel with E50 series welding material, when two different steel connected, under the premise of ensuring weldability can be used with low-strength steel welding material. The welding rods, wires and fluxes used in this project shall be compatible with the mechanical properties of the main metal and shall meet the corresponding current national standards.

(b) Bolts

The common bolts used in this project are grade C bolts, and the high-strength bolts are all grade 10.4, and the anti-slip coefficient of the friction surface is 0.446. The high-strength bolts shall comply with the current national standards of High-strength Large-hexagonal Head Bolts for Steel Structure GB/T 1228-2006, High-strength Large-hexagonal Nuts for Steel Structure GB/T 1229-2006, High-strength Washers for Steel Structure GB/T 1230-2006, High Strength Large Hexagonal Head Bolts, Large Hexagonal Nuts and Washers for Steel Structures and Technical Conditions GB/T 1231 or Torsion and Shear High Strength Bolts for Steel Structures GB/T 3632-2008 and High Strength Bolts for Steel Structures Technical Specification JGJ 82-2011.

(c) Pin bearing.

Pin support: The material of the pin is 40Cr steel, which should meet the requirements of the current national standard “High Quality Carbon Structural Steel” GB/T 699-1999. All pins need to be heat-treated, and the hardness reaches (26-32) HRC.

Table 1: Mechanical property parameters of steel

Steel model	Q345B	Q235B	Unit
Elastic modulus	205500	205500	MPa
Shear modulus	81050	81050	MPa
Poisonby	0.6	0.6	-
Pressure resistance design value	286	208	MPa
Bending resistance design value	286	208	MPa
Shear resistance design value	165	118	MPa
Coefficient of thermal expansion	0.000024	0.000024	

II. A. 2) Project characteristics

(1) Analysis of the characteristics of the project. The summary analysis of the project has the following characteristics:

(a) construction site site is limited

The construction project in the internal construction construction, the work surface in the operable space is limited transportation capacity is poor, it is difficult to meet the transportation capacity of large steel components and mechanical equipment. The construction site requires lifting equipment to go back and forth, which increases the difficulty of stacking and installing large-span steel components.

(b) Multi-trades cross operation, high requirements for lifting operation

During the actual construction of large-span steel structure, the phenomenon of cross construction of different types of work is very common due to the rush of construction period. During the construction process of large-span steel structure, there are cases of steel structure lifting, installation construction and removal of temporary support at the same time, and during the construction process, the lifting equipment, installation equipment, on-site lines, and cross operation of different types of construction personnel increase the complexity of the construction site, so it is difficult to get very effective management, and the different construction operations may be affected by the lack of communication and exchanges. The common situation is in the crane running route stacked with steel structure components collision, monitoring process due to the construction personnel's touch leads to inaccurate data and other phenomena, resulting in the construction site has a great deal of arbitrariness, there is a potential risk of affecting the safety of the construction process.

(c) High welding process requirements

Welding quality has always been one of the important factors affecting the safety of steel structure. Welding and assembling of steel structure at high altitude increases the difficulty of workers' welding and puts forward higher requirements for welding process. Secondly, the steel pipe joist members are all thin-walled members, which are easy to produce welding residual stress due to the welding quality, and at the same time, it is easy to produce welding defects such as burn-through and biting edge. When welding at high altitude, the welders are required to ensure their own safety as well as the quality of welding.

(d) Poor structural stability during construction

The steel structure project has a large span which is prone to large deflection and deformation. Meanwhile, the installation of steel trusses of this project adopts the method of segmental lifting and then connecting at high altitude, so the overall rigidity of the structure is small in the process of construction and how to ensure the stability of the structure is more prominent, and how to accurately control the wind-resistant performance of the structure in the process of construction is also the key problem of this project.

(2) Analysis of wind resistance performance

This paper takes the large-span steel structure project as an example to study its construction process, the traditional structural design is for the use of the structure, and there is a big difference between the force performance of the structure in the construction phase and the use phase, in order to ensure the construction safety, it is necessary to carry out the analysis of dynamic characteristics of large-span wind-resistant performance of steel structure, which is aimed at improving the stability of the large-span steel structure.

II. B.Dynamic characterization of wind resistance

Finite element simulation can complete various working condition tests of large-span steel structures under ideal incoming flow conditions, simulate the flow field distribution characteristics in the area near the incoming flow through the structure, and facilitate the analysis of the dynamic characteristics of wind-resistant performance of the spanning steel structure. The details are as follows:

II. B. 1) Relationship between wind speed and wind pressure

In wind design studies of large-span steel structures, wind pressure is usually used to express the magnitude of wind loads acting on the structure. The value of wind pressure increases continuously with the increase of wind speed. The energy expression for an incompressible ideal fluid mass moving in the same horizontal plane can be written:

$$\omega_a V + \frac{1}{2} m v^2 = C \tag{1}$$

where $\omega_a V$ is the hydrostatic energy. $\frac{1}{2} m v^2$ is the kinetic energy. C is a constant. ω_a is the hydrostatic pressure per unit area. V is the volume of the air mass. v is the wind speed. m is the mass of the moving fluid mass. Then the wind pressure generated by the action of the free-flowing gas per unit area of the structure can be obtained from the above energy expression:

$$\omega = \frac{1}{2}\rho v^2 \tag{2}$$

where, ρ is the density of the air mass.

II. B. 2) Wind pressure coefficient

In general, the average wind pressure coefficient at a given time interval can be expressed as:

$$C_p = \frac{\overline{P}}{0.5\rho U^2} \tag{3}$$

where, $\overline{P}$ is the mean wind pressure. $\rho = 1.29$ Kg/m³. U is the average wind speed.

The coefficient of pulsating wind pressure at a certain time interval can be expressed as:

$$C_p^{'} = \frac{P^{'}}{0.5\rho U^2} \tag{4}$$

where, $P^{'}$ represents the root mean square of the pulsating wind pressure.

II. B. 3) Static three-part force coefficients

For the structure section located in the wind field, if the effect of structural self-oscillation is not considered, it can be regarded as a rigid body fixed in the wind field to remain immobile. When the free-flowing gas passes through the rigid structure, it will produce the phenomenon of gas bypassing the structure, which causes the change of the distribution of flow lines. Then on any streamline, according to Bernoulli's equation can be obtained:

$$\frac{1}{2}\rho U^2 + P = \text{Constant} \tag{5}$$

where, ρ is the air density, U is the incoming flow velocity, and P is the pressure.

Then, the flow velocity at the point with larger value of pressure on the structure surface will be smaller than the flow velocity at the point with smaller value of pressure on the structure surface. The resistance load of the wind load on the structural section is equal to the horizontal component of the integral value of the pressure on the structural surface. The lift load is equal to the vertical component of the integral value of the pressure, and the value of the lift load on the structural section can also be obtained by conducting wind tunnel tests on the segmental model. In addition to this, the structural section is also subjected to torsional moments since the combined drag and lift forces do not act on the form center of the structural section.

Fig. 1 shows the three-fold force of the structural section under wind loads which are usually represented in two ways, one is defined by the wind-axis coordinate system, i.e., the lift force F_L, the drag force F_D, and the torque M_T. The second is based on the body-axis coordinate system of the structure section itself, i.e., lift F_V, drag F_H and torque M_T.

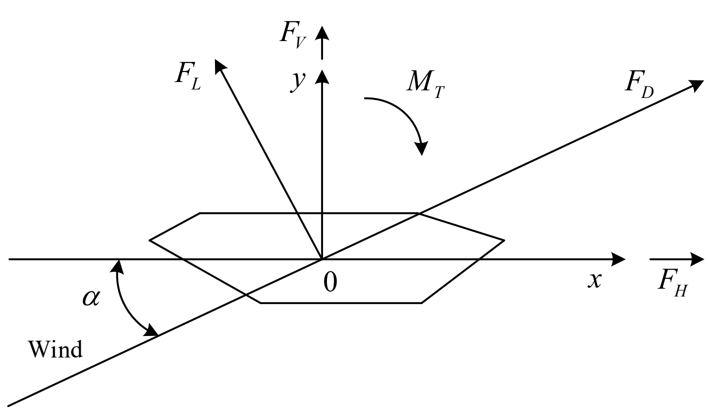


Figure 1: Three-component forces of the structural section

Obviously, the torque M_T of the structural section is the same in both different coordinate systems, and the expression of the transformation relation between (F_L, F_D) and (F_V, F_H) is given by:

$$F_V = \cos\alpha \cdot F_L + \sin\alpha \cdot F_D \tag{6}$$

$$F_H = -\sin\alpha \cdot F_L + \cos\alpha \cdot F_D \tag{7}$$

In order to describe the same force characteristics of structural sections with the same cross-sectional shape under the action of static wind load, a dimensionless quantity, i.e., the coefficient of static three-component force, can be defined based on the fact that the static wind load on two structural sections with similar cross-sectional shapes should be proportional to the characteristic dimensions of their cross-sections under the condition of other conditions being the same. Then using this dimensionless quantity, the expression for the three components of the static wind load on the structural section expressed through the body-axis coordinate system is:

Resistance:

$$F_H = \frac{1}{2}\rho U^2 C_H DL \tag{8}$$

Lift:

$$F_v = \frac{1}{2}\rho U^2 C_v BL \tag{9}$$

Torque:

$$M_T = \frac{1}{2}\rho U^2 C_M B^2 L \tag{10}$$

where, U is the average wind speed far upstream of the structural section, ρ is the air density, C_H, C_V, C_M are the drag coefficients, lift coefficients, and torque coefficients expressed through the body-axis coordinate system, respectively: and D, B are the height and width of the structural section, respectively.

For the static three-part force coefficient can also be understood in this way, that is, taking the drag force as an example, the dynamic pressure loss due to the obstruction of the incoming gas on the structural section is the product of the dimensionless C_H and the dynamic pressure of the incoming gas $\frac{1}{2}\rho U^2$, and this dynamic pressure loss is converted into the static pressure of the structural section, and then the structural section length per unit of resistance can be expressed as the product of this static pressure and the height of the section [21], [22]. Similarly, the three components of the static wind load on the structural section in the wind-axis coordinate system can be expressed as:

Resistance:

$$F_D = \frac{1}{2}\rho U^2 C_D DL \tag{11}$$

Lift:

$$F_L = \frac{1}{2}\rho U^2 C_L BL \tag{12}$$

Torque:

$$M_T = \frac{1}{2}\rho U^2 C_M B^2 L \tag{13}$$

where, C_D, C_L, C_M are the drag coefficients, lift coefficients and torque coefficients expressed through the wind-axis coordinate system, respectively. Therefore, the expression for the static three-part force coefficient is:

Drag coefficient:

$$C_D = \frac{F_D}{0.5\rho U^2 DL} \tag{14}$$

Lift coefficient:

$$C_L = \frac{F_L}{0.5\rho U^2 BL} \tag{15}$$

Torque coefficient:

$$C_M = \frac{M_T}{0.5\rho U^2 B^2 L} \tag{16}$$

The conversion relationship between the static three-part force coefficients in the body-axis coordinate system and the wind-axis coordinate system can be obtained by the conversion as follows:

$$C_D = C_H \cdot \cos\alpha + C_V \cdot B / D \cdot \sin\alpha \tag{17}$$

$$C_L = -C_H \cdot D / B \cdot \sin\alpha + C_V \cdot \cos\alpha \tag{18}$$

The above equation shows that the static threefold force coefficient is a function of the angle of attack α and that the static wind load on the structural section is related to the wind angle of attack α .

II. C.Finite element modeling of span steel structures

II. C. 1) The finite element method

The finite unit method is referred to as the finite element method, and its basic idea is to turn the whole into zero, and the accumulation of zero into the whole, that is to say, the continuous structure is first discretized into a finite number of units, and then a finite number of nodes are set up in each unit, and finite element equations are established by using the principle of mechanics, so as to transform the continuous infinite degree of freedom problem into a discrete finite degree of freedom problem [23], [24]. After obtaining the results, these units are then combined back to the original form to calculate and analyze the structure as a whole. The net frame structure is generally formed by beam members through rigid or articulated connections, which can be simulated by using a space beam rod system for finite element simulation. Usually, the following assumptions need to be satisfied in the process of modeling:

(1) The nodes of the net frame structure are considered to use fully articulated or stiffened space nodes, the former with three degrees of freedom and the latter with six degrees of freedom.

(2) The overall damping of the structure is small and satisfies the Rayleigh damping assumption, i.e., it satisfies the linear combination of the mass matrix and the stiffness matrix.

(3) In addition to the self-weight, the load effects on the structure can be equivalently applied to the nodes through the linear transfer of materials, and the wind load can be applied to the structure by applying the node loads. When modeling, the 3D3S software model is chosen to be drawn as a transition, and then imported into the ANSYS finite element software for wind dynamic characterization of the structure.

II. C. 2) Analytical software

(1) 3D3S Software

3D3S steel and space structure design software is a CAD series software, developed by Tongji University, which can draw many types of structures including light steel structure, truss and network structure, high-rise building structure, etc., and generate CAD design construction drawings and calculation book documents. The software is based on AutoCAD graphic platform, closely integrated with the commands in CAD software, and the operation methods of both are basically the same. However, the specific drawing process of 3D3S is more simple, and it can classify and number the nodes and bar types, so as to carry out classification and editing. After the graphics are drawn, the interface program can be interfaced with the finite element software to achieve data sharing, so that the CAD model diagram can be converted into a MAC command flow format that can be used in ANSYS analysis software.

(2) ANSYS software

ANSYS finite element software is a set of structural, thermal, acoustic, fluid, electromagnetic and coupled field analysis as one of the large-scale general-purpose software. The software has been widely used in various engineering fields, and has become a big help in solving complex engineering problems.ANSYS software has powerful modeling ability and solving ability, powerful and easy to use, and is the first choice of software for simulating the dynamic characteristics of wind-resistant performance of large-span steel structures. In the process of using ANSYS software, it has two modes of use, which are the GUI mode with the mouse on the menu and the GUI mode with the dialog box selection.

The two modes of use are the GUI mode of dialog box selection and the command flow mode of inputting command flow text. Among them, the command flow mode integrates APDL, UPFs, MAC and other modes, and it is easy to read and execute commands by inputting text, which is convenient for modifying, communicating and saving the structure, and greatly simplifies the operation steps and improves the operation efficiency.

II. C. 3) Model construction

The net frame adopts the positively placed quadrangular cone system, which is arranged in such a way that the force is uniform, the spatial rigidity is large, and it is easy to fabricate and install. The structure selects the upper and lower chord double-row bracing method. At present, single-row diagonal bracing is usually adopted for the 200m or so span net frame structure. However, for the net frame structure with large wind load and span more than 200m, the double-row top and bottom chord bracing with better stiffness can make the net frame structure obtain better stability and safety. With the open ends of the mesh frame structure and the coal pile inside, the structure has a large span and small damping, and the wind load will have a more significant effect on the stress of the structure. Therefore, it is quite important to study the wind resistance of the structure. The finite element model used in the study is a structural model that can be used for subsequent analysis and calculation by drawing CAD graphics according to the actual structural distribution of the project, then converting to the finite element analysis ANSYS software through the interface, and fine-tuning the ANSYS model according to the actual situation. All the rods in the model are made of circular welded steel pipe Q345 steel, and are modeled by three-dimensional space beam units, with a total of 8,718 nodes and 29,946 rods in the whole model, and the structure is articulated with the type of support being three-way fixed support. The modulus of elasticity of the rod material in the model is 2.052×1011 Pa, Poisson's ratio is 0.292, coefficient of thermal expansion is 1.17×10-5, and the yield limit is 228 MPa.Before carrying out the study, it is firstly stipulated that: the direction along the long side of the structure is the X-direction of the structure. The direction along the span of the structure is the Y direction of the structure. The direction along the height of the structure is the Z direction of the structure. In the process of wind load application, from the zero point of coordinates, the wind angle is 0° along the positive direction of X, 90° along the negative direction of Y, and so on.

III. Simulation of dynamic characteristics of wind-resistant performance and improved design

III. A. Analysis of wind bearing capacity of long-span steel structures

III. A. 1) Load-bearing capacity check

In recent years, typhoons occur frequently, and some buildings are seriously damaged, reflecting the dynamic characteristics of wind resistance of long-span steel structures. Since there is no ready-made specification for reference in the calculation of typhoon resistance, and the owner has not specified the performance target of typhoon resistance design, in order to consider reducing the economy of the project and meet the requirements of typhoon resistance design, the design team of the project proposes to carry out typhoon resistance design according to the performativity, and the performance level of the load bearing capacity is Ac level, i.e.: all the members are in elasticity under the action of moderate wind according to the specification design. Under typhoon, the key components are elastic, and the general components and enclosure components are designed without yielding. Since the project is designed as an ordinary structure according to the current code under the effect of moderate wind, it is not described here. In the design of this project, the columns supporting the roof cover are designed to be elastic under typhoon, and the reinforcement of the net frame supporting columns is calculated according to the elasticity. The mesh frame columns and enclosure members were designed using non-yielding. Due to the uncertainty of the effect of constant load on the structure under typhoon, the constant load combination is carried out according to unfavorable and favorable respectively, the combination coefficients are 1.193 and 0.823, and the wind load combination coefficient is 1.008, and the specific combination coefficients are shown in Table 2. Referring to the mid-seismic unyielding design under seismic action, the standard value of the material is used for the calculation of the load capacity of the members under the action of typhoon, and the corresponding wind load adopts the converted standard value of 2.225kPa under the typhoon of grade 16.5.

Table 2: Typhoon load combination coefficient

Combination number	DL	WT0	WT90	WT165	WT270
1.193DL+WT0	1.193	1			
1.193DL+WT90	1.193		1		
1.193DL+WT165	1.193			1	
1.193DL+WT270	1.193				1
0.823DL+WT0	0.823	1			
0.823DL+WT90	0.823		1		
0.823DL+T165	0.823			1	
0.823DL+WT270	0.823				1

The results of the above combinations and conditions of the checks are shown in Fig. 2, and it can be seen that, so all the main steel members' load carrying capacity can satisfy the performance objective of not yielding. The concept of calculating the performance-based wind design idea is used in the design of large-span steel structure. While ensuring the safety of the main structure, it effectively reduces the cost of the owner and the difficulty of construction. From the beginning to the successful completion of this project, and from the commissioning to the operation to date, the project has experienced the attack of the eye of the typhoon of magnitude 16.5, with a central wind of 57.5 m/s. After the typhoon, the roofs of the other venues were damaged in a large area, but there was only slight damage to the accessory components in this project, which can meet the requirements of the original design of the Ac level of wind-resistant performance targets. The performance-based design method is an advanced design method, and it is necessary to expand it from the seismic design category and apply it to the structural design of more and more broad fields. However, the current research on wind-resistant performance-based is not perfect enough, and a great deal of research work is still needed to advance the wide application of this methodology.

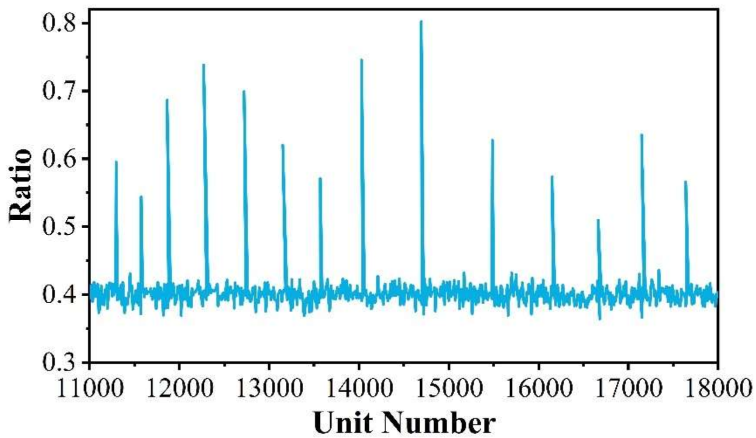


Figure 2: Verification results of steel components

III. A. 2) Limit state load analysis

By analyzing the wind load bearing capacity of the large-span steel structure when it reaches the limit state, the results show that the maximum displacement of each stick stiffener mostly occurs at the ridge position, and the displacements along the three directions at the ridge of each stick stiffener at the limit state and the total displacements at each place are given in Table 3, in which X1, Y1, Z1, and T1 denote the displacements and total displacements of the diagonal-directed wind stiffeners in the outward direction of the face, the inward vertical direction of the face and the horizontal direction of the face, respectively, X2 In the table, X1, Y1, Z1 and T1 represent the displacement and total displacement of the wind rigid frame in the outward direction of the inclined direction, vertical and horizontal direction of the face, respectively, and X2, Y2, Z2 and T2 represent the displacement and total displacement of the wind rigid frame in the front direction. As can be seen from Table 3, the out-of-plane displacement of the large-span structure under the action of oblique wind is obviously larger than that under the action of frontal wind, and the total displacement value synthesized by the three direction vectors is also larger than that of the latter in general. The out-of-plane displacements are small in the case of forward wind, but the in-plane lateral displacements and vertical deflections are larger, which are basically in the same order of magnitude. The displacement results indicate that the large-span steel structures have larger out-of-plane displacements under oblique winds, which may make them more susceptible to out-of-plane localized or overall instability, and thus more susceptible to loss of structural load-bearing capacity.

III. B. Wind Stability Analysis

III. B. 1) Analysis of the whole process of static wind instability

The proposed cable-stayed bridge is subjected to a static wind at 0° wind angle of attack, with a starting wind speed of 30 m/s and a wind speed increment of 20 m/s.

(1) Calculation of state static wind instability

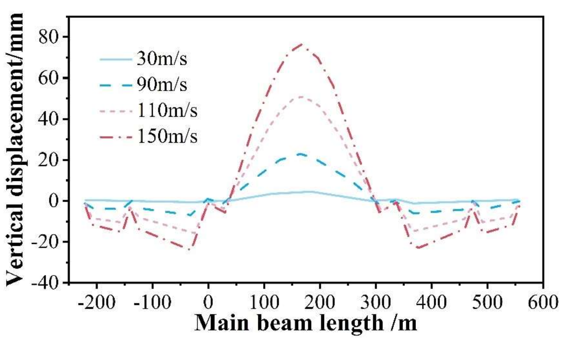
Figure 3 gives the main girder vertical and lateral displacement and torsion angle wind speed change curve, where (a) ~ (c) are the main girder vertical and lateral displacement, torsion angle, Table 4 gives the main girder displacement response in the main span with different wind speeds. The graphical observation shows that with the increase of wind speed, the main girder mid-span displacement varies in a small range, and when the ambient wind speed reaches 110 m/s, the mid-span vertical displacement increases from the initial 3.45 mm to 75.25 mm, the transverse displacement increases from 41.22 mm to 469.2 mm, and the angle of torsion increases from 0.211° to 2.669°. The results in the table show that the transverse displacement and torsion angle are more sensitive to the change of wind speed, showing a linear increase. When the wind speed increases from 110m/s to 150m/s, the main girder span-to-span deformation no longer varies with the wind speed and a stabilization stage occurs. When the wind speed increases to 170m/s, the mid-span deformation instantly changes to infinity, and the main girder structural displacement dispersion phenomenon occurs, resulting in the large-span steel structure destabilized by the static wind.

Table 3: Displacement at the ridge of the rigid frame under oblique wind load

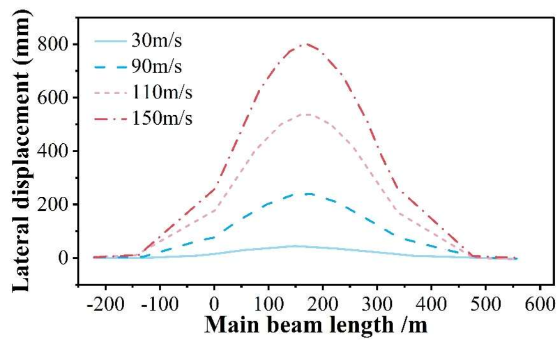
N	0.823DL+WT0	0.823DL+WT90	0.823DL+T165	0.823DL+WT270	1.193DL+WT0	1.193DL+WT90	1.193DL+WT165	1.193DL+WT270
X1	-29.45	-32.25	-31.66	-30.45	-30.07	-29.22	-28.15	-30.15
Y1	0.014	207.25	231.21	224.35	217.24	236.35	196.31	158.2
Z1	10.25	13.35	46.05	55.33	57.25	57.41	41.22	11.09
T1	31.35	210.25	238.05	233.25	226.45	245.05	245.22	202.45
X2	-0.172	-1.611	-1.336	-0.805	-0.253	0.253	0.264	1.315
Y2	0.414	139.35	160.25	157.15	157.03	157.09	157.09	160.25
Z2	-43.35	-49.45	-119.25	-140.44	-145.25	-145.25	-145.25	-119.25
T2	43.35	148.22	200.05	214.05	214.05	214.05	200.05	148.15

Table 4: Main beam displacement response

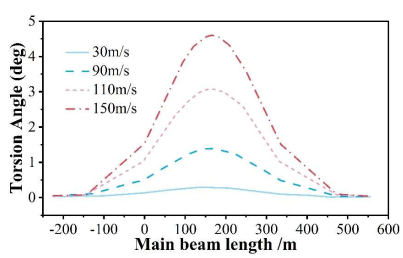
Wind speed (m/s)	Vertical displacement (mm)	Lateral displacement (mm)	Torsion Angle (deg)
30	3.45	41.22	0.211
50	10.28	105.45	0.607
70	30.33	200.15	1.091
90	45.05	317.2	1.842
110	75.25	469.2	2.669
130	75.25	802.2	4.537
150	75.25	802.2	4.568
170	82262444.4	660924512.5	3743691.5



(a)Vertical displacement



(b)Lateral displacement



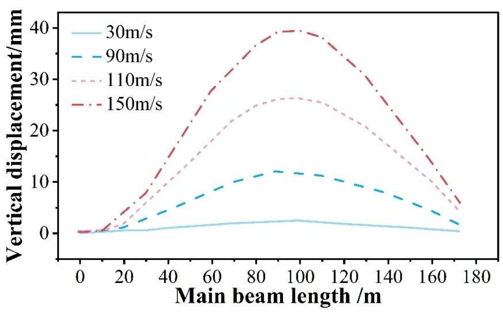
(c)Torsion Angle

Figure 3: Displacement of the main beam under calm wind conditions

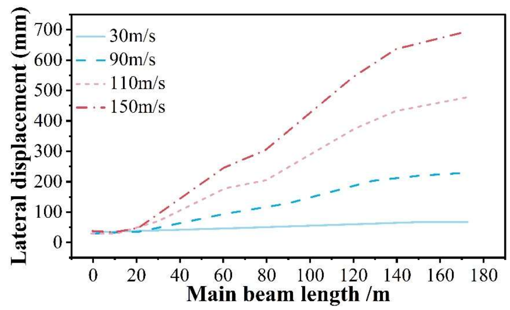
Table 5 gives the top of tower and 2/5 tower height displacement response for different wind speeds, and Fig. 4 gives the displacement response for different wind speeds at each node of the main tower. Analyzing the graphs, it can be seen that all the transverse bridging displacements of the main tower under crosswinds increase rapidly with the increase of wind speed. The longitudinal bridging displacement of the main tower increases with the wind speed level, and the longitudinal displacement at 2/5 tower height starts to increase significantly, and the longitudinal deformation at the top of the tower is small, which indicates that the main tower body bends to the mid-span. Combined with the main girder mid-span deformation, it can be seen that the wind speed increases, the main girder mid-span deformation is large, the mid-span diagonal cable on the main girder constraint weakened, the top of the tower tends to the side of the side span side, and the two main towers bend to the mid-span. When the wind speed is 170m/s, the displacement of the main tower suddenly disperses, and the bridge structure undergoes static wind instability damage. This is consistent with the phenomenon that the main girder shows sudden dispersion at the critical wind speed (170m/s).

Table 5: Wind speed and displacement response

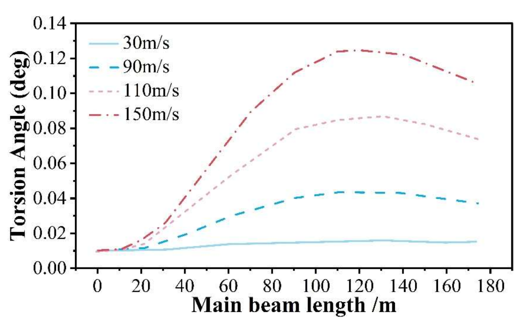
Wind speed (m/s)	Longitudinal bridge displacement (mm)		Transverse bridge displacement (mm)		Torsion Angle (deg)	
	Two fifths of the tower height	Top of the tower	Two fifths of the tower height	Top of the tower	Two fifths of the tower height	Top of the tower
30	2.042	0.287	17.05	35.33	0.00535	0.00522
90	11.342	1.665	98.35	205.05	0.003235	0.03045
110	25.637	3.776	222.05	461.25	0.07325	0.06922
150	38.294	5.584	331.44	689.22	0.10944	0.10335
170	30400234.1	-7101546.4	189084844.8	218383100.3	90338.5	78233.1



(a)Vertical displacement



(b)Lateral displacement



(c)Torsion Angle

Figure 4: Displacement throughout the entire process of static wind instability

(2) Calculation of static wind instability for construction of maximum single cantilever state

Table 6 gives the displacement response of the cantilever end of the main girder at different wind speeds, and Table 7 gives the displacement response of the main tower at the top of the main tower and at the height of 2/5 tower at different wind speeds. Figs. 5 and 6 give the displacement curves of the main girder and the main tower with the change of the wind speeds, in which (a) to (b) are the longitudinal bridge displacement and the transverse bridge displacement, respectively. Observing the graphs, it can be seen that when the wind speed reaches 270m/s, the transverse displacement of the cantilever end of the main girder reaches 2.38044m, which is 33.6012 times of the initial wind speed, the torsion angle of the cantilever end of the main girder reaches 13.72°, which is 33.5022 times more, the vertical displacement of the cantilever end of the main girder reaches 0.50405m, which is 32.6014 times more, and the transverse bridging displacement of the top of the main tower reaches 1.2425m, which is 25.0027 times of the initial wind speed. It can be predicted that if the wind speed further increases to the critical wind speed, the main girder and the main tower will have transverse displacement dispersion phenomenon leading to the destabilization of the structure. The main girder is destabilized by a complex combination of horizontal and vertical bending and torsion, while the main tower is destabilized by lateral bending. By analyzing the whole process of static wind destabilization of the inclined long-span steel structure under 0° angle of attack and the construction of the largest single cantilever state, the mechanism of static wind destabilization of the long-span steel structure is derived.

(1) The static wind load has the greatest influence on the lateral response of the main girder and the main tower, and the wind speed increases, and the lateral displacement of the large-span steel structure increases significantly.

(2) When the wind speed does not exceed the critical wind speed, the long-span steel structure can resist the wind response through the resistance generated by its own deformation, and reach the stable state of the structure.

(3) The deformation of the main girder structure under the action of transverse wind is dominated by transverse bending, and the vertical bending and torsion are smaller. The main tower structure is mainly transverse bending, and according to the results of modal analysis, this phenomenon coincides with the first three orders of the modal state of the bridge structure. The main girder and main tower transverse bending as well as the main girder vertical bending modes appeared earliest, and the torsional modes of the main girder appeared later. The possibility of linear torsional divergence of the main girder is lower, and it is more likely to occur the combination of bending and torsional instability.

(4) When the wind speed reaches the critical wind speed, the large-span steel structure can not maintain the stable state through its own deformation, and the displacement dispersion phenomenon occurs, and the structure is destabilized by the static wind. At this time, the lateral displacement of main beam and main tower is infinite, accompanied by the vertical and torsional displacement of main beam, presenting a spatial bending and torsion combination pattern.

Table 6: Displacement of the cantilever end of the main beam at different wind speeds

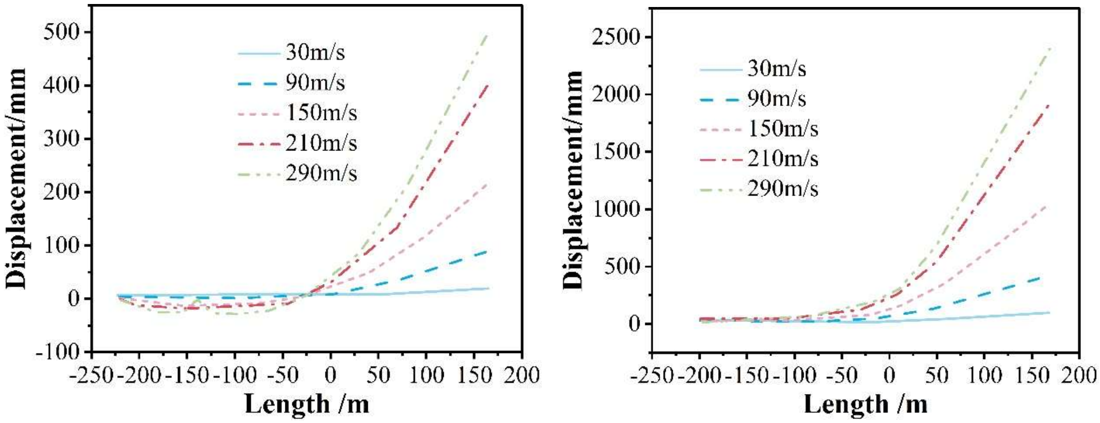
Wind speed (m/s)	Vertical displacement (mm)	Lateral displacement (mm)	Torsion Angle (deg)
30	14.92	70.44	0.33
90	86.15	407.35	2.37
150	216.22	1022.08	5.45
210	405.14	1913.35	11.05
290	504.05	2380.44	13.72

Table 7: Wind speed and displacement response

Wind speed (m/s)	Longitudinal bridge displacement (mm)		Transverse bridge displacement (mm)		Torsion Angle (deg)	
	Two fifths of the tower height	Top of the tower	Two fifths of the tower height	Top of the tower	Two fifths of the tower height	Top of the tower
30	-23.17	-140.33	18.44	49.33	0.0088	0.0123
90	-9.42	-143.45	102.25	223.15	0.0515	0.0665
150	14.27	-150.08	255.07	540.3	0.1315	0.1684
210	49.35	-158.45	476.25	999.35	0.2504	0.3158
290	68.14	-163.34	592.25	1240.25	0.3094	0.3915

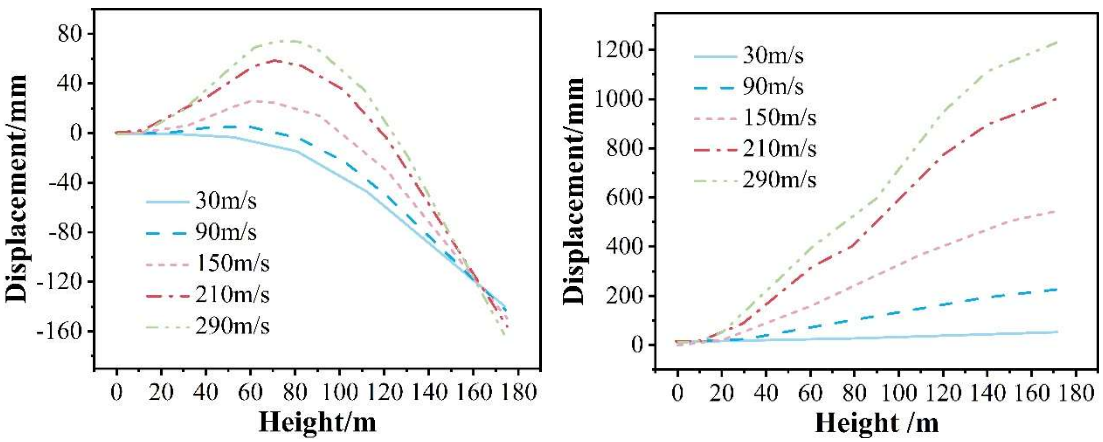
III. B. 2) Analysis of the effect of initial wind angle of attack on static wind stability

Tables 8 and 9 list the critical wind speeds of bridge structures at different wind angles of attack and the displacement response to the critical wind speed of instability in the bridge state. The critical wind speed at different angles of attack of the large-span steel structure destabilized in different patterns, the bridge structure is sensitive to the change of the wind angle of attack, 0 ° wind angle of attack critical wind speed of the main girder of the transverse and vertical, torsion displacement and the main tower of the longitudinal and transverse, torsion displacement are dispersed, appearing in the space of the combination of bending + torsion pattern. -The main beam and the main tower at 5° and 5° angle of attack critical wind speeds were destabilized by transverse bending.



(a)Vertical displacement (b)Lateral displacement

Figure 5: Displacement of the main beam in response to static wind



(a)Longitudinal bridge displacement (b)Lateral displacement of the bridge

Figure 6: The displacement of the main beam in response to static wind

Table 8: Critical wind speed responses of main beams at different wind attack angles

Wind attack Angle (deg)	Critical wind speed Vcr(m/s)	Lateral displacement (m)	Vertical displacement (m)	Twist Angle (deg)
-5°	170	66.42	-0.772	379.25
0	170	660923.51	82512.49	3743691.51
5°	170	66.33	-0.113	378.33

Table 9: Responses to critical wind speeds at different wind attack angles

Wind attack Angle (deg)	Critical wind speed Vcr(m/s)	Lateral displacement (m)	Vertical displacement (m)	Twist Angle (deg)
-5°	170	3.852	128.735	10.05
0	170	-7101.545	214338.12	78233.12
5°	170	3.627	128.37	9.984

III. C. Improved design

III. C. 1) Improvement of key design techniques and critical points

(1) Novel space tube joist scheme and reasonable structural stress: It is the first time that triangular tube joist columns and triangular tube joist beams are used in large-span steel structure building to form a space portal transverse stress overall, with standardized setting of the rods, and the node loads are borne by multiple rods, which are connected with each other and the overall stability is high. The overall strength of the pipe truss structure is

high, with the characteristics of tensile, bending and torsion resistance. In the appearance design, the shape is diversified and rich in modeling. In the process of structural construction, the structure is light in weight, and it is convenient to hoist, flip and splice, and the structure adopts rod to rod connection, which saves material. Moreover, tube truss structure saves certain amount of works by optimizing part of supporting and connecting members than net frame structure in design. Besides, because tube truss structure adopts three-dimensional design, it has rich structural styles, which can meet the demands of different functional buildings, and the advantages are more prominent in the design of arched and curved structures.

(2) The space pipe truss scheme has beautiful shape and saves building space: after optimization, the axial dimension of indoor DC field building is reduced to 70m×120m×40m, with a building area of 7500m².

(3) It provides strong technical support for improving the arrangement conditions of electrical and HVAC equipment and saving indoor floor space, provides strong safety guarantee for the operation of the equipment, and plays a positive role in improving the wind resistance performance.

III. C. 2) Construction key technologies and critical points

(1) steel column foundation using pre-embedded foot bolt reinforced concrete foundation, each foundation has a foot bolt and bolt on the upper part of the reinforced concrete small short column, in the foundation construction needs to be foot bolt and, small short column rebar rebar insertion pre-embedded. Then in the steel column in place, due to the small short column cross-section size of only 25cm, workers are inconvenient to operate, and a column has 20 bolts and 60 nuts, so in the construction process to develop a special foot nut tightening tool, easy for workers to operate, can be fast for bolt tightening work.

(2) Because of high-altitude splicing, the steel components swing a lot and are not easy to be accurately positioned, the site in the mouth of the pipe fittings to increase the mismatch adjusting parts, the use of special tools to accurately adjust the position of the butt-welding rods to speed up the speed of installation, saving the time occupied by the crane to improve the installation → butt-welding → welding of the one time the success rate, and the interface butt-welding fittings are accurate and error-free.

(3) In general steel structure project, in order to ensure the transportation at the construction site, it is necessary to divide the extra-long steel columns into several sections to be transported to the site, and then carry out lifting in sections and splicing in the air.

(4) Installation of additional sub-truss quick connecting plate

According to the requirement of improved design, fast positioning connection plate is set up at the end of secondary joist beam between columns and at the end of connection of steel column body, during construction, secondary joist and column are set into butt joints, and then fixed by bolts, the crane can be loosened, which ensures that there is no bad weld in the air, and the crane and other mechanical equipments can be quickly transferred to the next process.

(5) Overall lifting of large-span steel girders

But according to the site situation, the site is more compact, the whole construction site is only 40m larger than the building size range, and double machine lifting site command coordination is more complex, the two sets of machinery synchronization requirements are higher, in addition there is a slow speed of lifting, occupying the construction surface, can not be quickly carried out under the beam of the ground assembling.

(6) Overall lifting of wind-resistant column

Indoor DC field wall wind column, the length of 50m, structural form of two round tubes in the middle of the zigzag connecting rod piece structure, long and thin is relatively large, easy to flip and deformation when lifting, while the conventional construction program requires three cranes were lifting wind column column column head, column, column tail.

IV. Conclusion

By analyzing the dynamic characteristics of wind resistance of long-span steel structures, the following conclusions are drawn:

The mechanism of static wind destabilization of the large-span steel structure is as follows: the wind speed has the most significant influence on the lateral response of the main girder and the main tower, and when the wind speed increases but does not exceed the critical value, the structure can be stabilized by its own deformation and resistance; when the wind speed reaches the critical value of 170m/s, the structure can not be stabilized, and the transverse displacement in the span of the main girder changes from 469.2mm to 660923.51m, and the displacement dispersion phenomenon leads to the destruction of the structure. The phenomenon leads to structural damage.

The wind angle of attack has a significant effect on the static wind stability of the structure, and the structure shows a combination of spatial bending and torsion instability under the 0° wind angle of attack, while it mainly shows lateral bending instability under the ±5° angle of attack. Under the maximum single-cantilever condition of construction, the lateral displacement of the cantilever end of the main girder reaches 2380.44mm when the wind speed reaches 290m/s, which is 33.6 times more than that of the initial wind speed condition, indicating that the wind-resistant performance is weaker during the construction stage.

Limit state analysis shows that the out-of-plane displacement of the structure under oblique wind is obviously larger than that under forward wind, and the total displacement value is also larger than that of the latter, which is more likely to lead to the out-of-plane instability of the structure.

Adopting the improved design scheme of triangular tube truss columns and beams forming a spatial portal transverse force whole, combined with the optimization of construction technology such as quick connecting plate and overall lifting, the wind resistance of the structure was effectively improved, and the project was only slightly damaged by the accessory members after the eye of a 16.5 magnitude typhoon, which verified the validity of the design scheme.

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