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The Construction Technology of Freeform Surface Spatial Bending-Torsion Steel Structure

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Abstract: Taking the construction project of the National Cybersecurity Talents and Innovation Base as an example, this paper studies the construction technology of freeform surface spatial bending-torsion steel structure based on structural design model transformation, including the parametric modeling of deepening design model, computer-aided bending and torsion frame production, flexible docking in the bending-torsion combination unit, and welding stress deformation, in hope to provide reference for similar projects in the future.

Keywords: Freeform surface; Spatial bending-torsion steel structure; Construction technology; Parametric modeling; Bending and twisting frame

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1. Introduction

Since the 20th century, with social and economic development, growing cultural diversity and consumer demand, as well as the increasing influence of digital technology, curved surface architecture has seen an unprecedented development. It has allured architects, engineering construction personnel, and people from all over the world. Designing and constructing spatial curved and twisted buildings present great challenges to the construction team [1-3]. In recent years, a number of scholars have conducted extensive research on curved surface architectural design theory and construction technology, aiming to improve the construction efficiency of such buildings.

Based on Phoenix International Media Center project and finite element analysis, Wu Wenping and several researchers investigated spatial bending and torsion steel structure characteristics, the design of layout temporary support, the construction process, and support deformation [4]. In another study, several researchers studied the ground assembly technology and step unloading technology of spatial bending and torsion steel frame; combined with actual monitoring data, the accuracy of finite element method in calculating the displacement of each stage in the installation process of spatial bending and torsion steel structure was verified [5]. Zhao Qingke and other researchers studied the manufacturing process of computer-aided spatial bending and torsion components; using the results of computer surface analysis, the pressure value of the equipment was adjusted to improve the manufacturing accuracy of box and triangular section components [6]. Yang and several researchers developed a CAD/CAM information transmission system based on the steel structure used in Sunshine Valley Expo, realized intelligent construction drawings based on the three-dimensional model of steel structures, and reduced the workload associated with deepening design [7]. Based on the characteristics of spatial bending-torsion steel structure, a number of researchers developed a parametric modeling program for the structure; through accurate section attribute definition, the error caused by using a unified section for mechanical analysis was averted, and the design accuracy of spatial bending-torsion steel structure was improved [8]. Zhang and several researchers realized a parametric modeling of freeform surface structure based on Rhino and Grasshopper software [9]. In another study, based on the freeform surface engineering of the ribbon structure at Hangzhou International Expo Center, an analysis was carried out on the typical hoisting unit, the mechanical response of the hoisting unit was given in the block hoisting process, and hoisting suggestions were put forward; they conducted a construction simulation on the assembly scheme of the ribbon grid structure and the unloading scheme of the structure, and obtained the mechanical response law of the structure [10].

In this paper, from the perspective of construction units, combined with the engineering practice of national cybersecurity talents and innovation base, the rapid modeling method of freeform surface steel structure deepening design, the parametric drawing of construction drawings, computer-aided jig assembly, internal flexible interface, welding stress and deformation control, as well as other processes are studied, in hope to provide practical reference for future similar projects.

2. Engineering situations

The National Cybersecurity Talents and Innovation Base is located in Wuhan Airport Economic and Technological Development Zone. It is a key layout project in the field of network security in China, undertaken by Wuhan, under the guidance and support of the Central Network Information Office. Its overall planning area is 40 square kilometers. It is a local "network security academy + innovation industry valley" base, which protects the national network security cost.

The steel structure of the project is a freeform surface structure formed by spatial bending and torsion steel grid combination. The overall layout is axisymmetric, and the plane shape is a square with both, length and width at 110 meters. The hyperbolic grid roof is composed of 308 steel box girders with longitudinal and transverse intersections. The steel grid roof gradually forms two elliptical shell cylinders in the middle from the spatial extension and progressive changing surface around, which is one of the supporting structures of the roof. The schematic diagram of the main structure of the project is shown in **Figure 1**. The members of the steel grid structure are 150 × 400 mm spatial bending and torsion parallelogram cross sections. The elliptical reticulated shell tube roots from the ground, which gradually bend and twist at an angle of 73° to 120° and connect with the whole roof to form a whole, as shown in **Figure 2**. The cross sections on both sides of the parallelogram of the steel grid structure members are perpendicular to the ground, and the upper and lower two surfaces are bending distortion surfaces. In this project, the section of the single rod is small; the welding is difficult and easily deforms. The rods are all spatial bending and torsion, and the arc of local bending and torsion is large. It is difficult to control the complete fitting between the arc of the rod and the theoretical arc during processing. The stress shrinkage caused by the welding process and the ambient temperature during processing will also cause a small deviation in the arc of the rod.

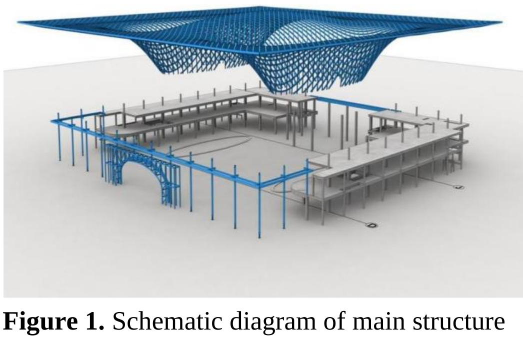

Figure 1. Schematic diagram of main structure

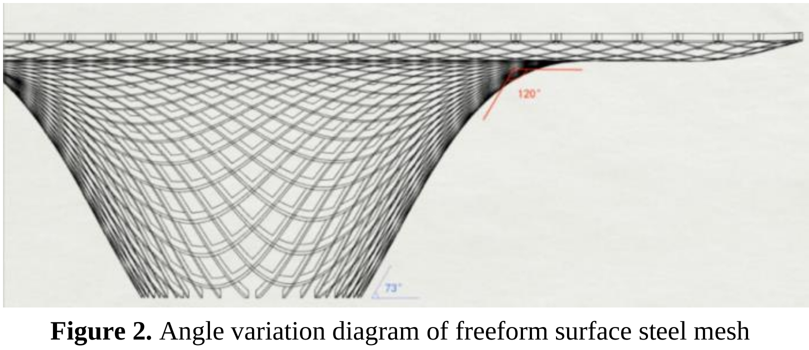

Figure 2. Angle variation diagram of freeform surface steel mesh

3. Rapid modeling technology of freeform surface spatial bending-torsion structure

3.1. Construction drawing deepening design model information modeling

This project involves many components, with difficult spatial positioning and enormous amount of work in the process of deepening design. In order to improve the efficiency of deepening design and avert invalid work or modeling error caused by repeated modeling, deepening design is conducted based on the three-dimensional line model established in midas Gen, which greatly reduces the workload.

The structural design software and construction drawing deepening design software used in this project are midas Gen and Tekla Structures, respectively. There is no direct interface between the two. However, the model in midas Gen can be exported in DXF format, and Tekla Structures accepts imports in this format. Based on the characteristics of both software, the information transmission between midas Gen and Tekla Structures is completed by virtue of AutoCAD in processing DXF files.

The first step is to obtain the structural design line model of the design institute. As shown in **Figure 3**, the design institute has used the model for finite element analysis and design checking calculation, and the model has high accuracy.

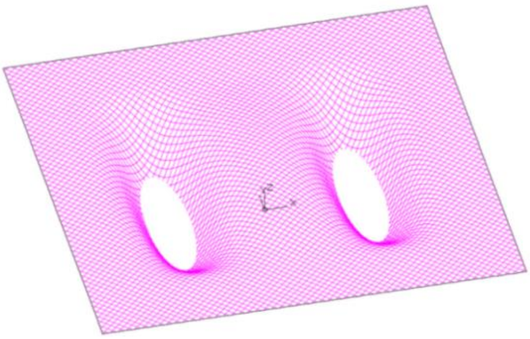

Figure 3. Schematic diagram of midas Gen line model

The second step is to set the parameters of the output line model in midas Gen. When imported into AutoCAD, as shown in **Figure 4**, the generated layer is divided by "characteristic value." When the DXF file is opened in AutoCAD, the section type number consistent with the midas Gen model file can be obtained, and the corresponding section type can be identified by numbering.

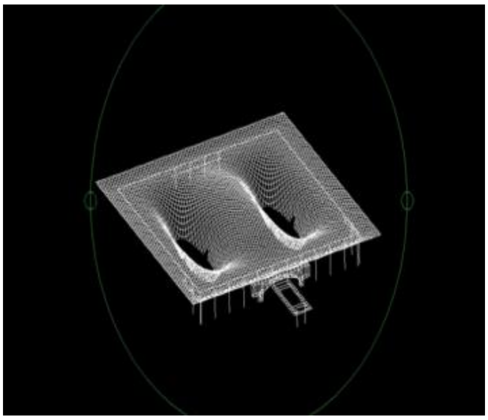

Figure 4. AutoCAD line model diagram

In the third step, the line unit data in the DXF file are input into Tekla Structures in layer. For each input layer, the section requires modification, so that the line unit data in the layer correspond to the section type. In that way, the workload of defining the section profile for the reference line can be omitted. Looping through each line unit turns all line units into solid models in Tekla Structures, as shown in **Figure 5**. Using this method, the deepening design modelling can be completed without size lofting and spatial positioning, and the working time and manpower can be reduced. The default length unit of midas Gen is m, while the default units of AutoCAD and Tekla Structures are mm, which need to be unified in the information transmission process.

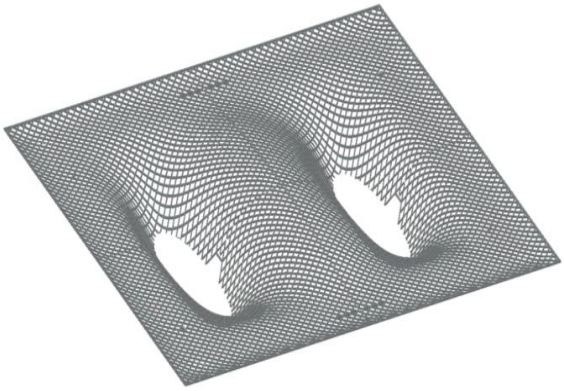

Figure 5. Tekla Structures solid model diagram

3.2. Parametric modeling of bending and torsion components

This project developed a plug-in system for secondary development based on CAD platform. The intelligent modeling plug-in system V1.0 can conveniently and efficiently realize the drawing and modeling of bending and torsion components. With C# language as the tool, the modeling and drawing process of the entire bending and torsion component will be as such: AutoCAD → Tekla Structures → AutoCAD. Combined with the development platform of Tekla Structures, the organizational structure and functional requirements of the software can be designed according to the geometric characteristics of the spatial bending and torsion component as well as special processing and installation requirements. The following functions can be realized: the spatial arbitrary curved surface bends and twists along the specified surface; the plane arbitrary curve projects to the surface; the spatial arbitrary curve webs perpendicular to the earth. In addition, the software package includes entity model query, steel report generation, three-dimensional coordinate generation and storage, bending and torsion component intelligent drawing output, as well as batch structure modeling. The plug-in can realize the full intelligence of model drawing, simple and convenient operation, batch operation, and greatly improve the deepening efficiency of bending and torsion components.

4. Computer-aided flexible multi-support external support assembling technology

The design of assembly frame is closely linked to the accuracy, safety, and economic practicability of truss ground assembly. This project uses the computer simulation assembly technology combined with structural design drawings and the actual construction site to simulate the tire frame assembly process. It also uses the computer-aided assembly technology to improve the accuracy of tire frame assembly.

The technical process of tire frame assembly is as follows: laying the ground sample → setting up a multi-point variable flexible tire frame → installing the lower wing plate → installing the web → welding the main rod and the secondary rod weld. In the first step of the project, according to the deepening design and construction drawings, relevant projection lines are drawn on the horizontal platform using computer control; they include the contour or projection lines of the main port, the lower wing plate, the two sides of the web, and other important control parts; the important positions are punched, as shown in **Figure 6**.

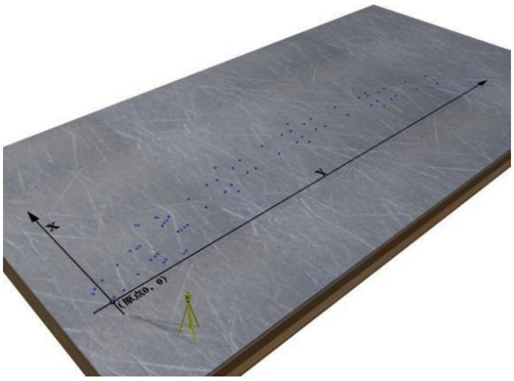

Figure 6. Computer lofting model

In the second step, according to the projection contour and control points, the adjustable frame is placed, and the horizontal plate is set up to minimize the height of the frame under the premise of ensuring the operability of assembly and welding. The height of the frame is leveled by the leveler, and the error is controlled within 1 mm. Due to the gradual surface of the rod, the frame can be adjusted by adjusting the variable flexible support frame to prevent repeated erection and save manpower and materials. A computer simulation of the tire frame assembly model is shown in **Figure 7**.

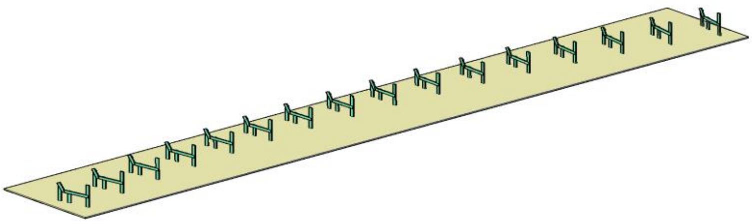

Figure 7. Computer simulation of tire frame assembly

The third step is to place the lower wing according to the position of the tire frame. After the lower wing plate is in place, the key control points are aligned to the coordinates and dimensions by using pyrotechnics and auxiliary external force equipment (wedge nails or jacks) with an error of less than 2 mm, and the control point error of its curvature is less than 5 mm, as shown in **Figure 8**.

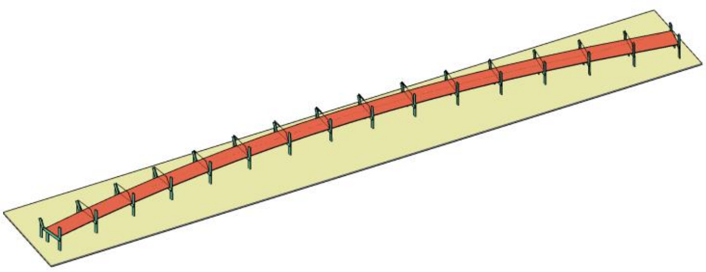

Figure 8. Simulation of wing plate installation

The fourth step includes positioning web 1, leading the coordinate points of the diaphragm floor sample to the upper surface of the lower flange plate of the box type by hanging plumb, and setting up the internal diaphragm. After partition positioning, web 1 is attached to the edge of the partition according to the location of the partition to achieve the effect of "internal support and external support" and is accurately located. The layout schematic diagram of the web partition and the installation simulation diagram of the wing plate under the web partition are shown in **Figure 9** and **Figure 10**, respectively.

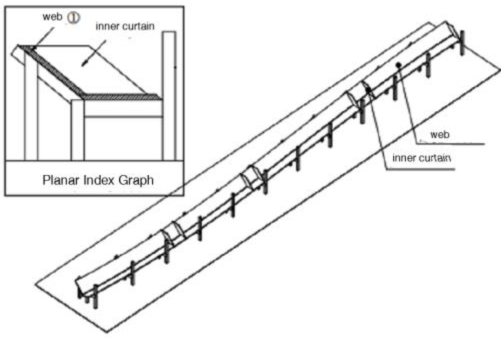

Figure 9. Layout of web partition

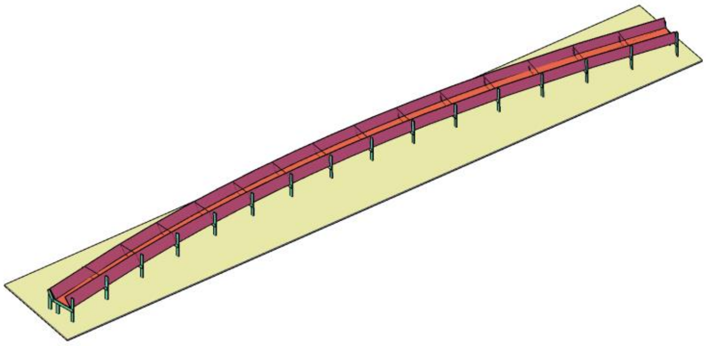

Figure 10. Simulation of wing plate installation under web partition

In the fifth step, web 2 and the upper wing plate are attached to the inner diaphragm's "lining outer support" assembly, and web 2 is set up according to the inner diaphragm. The web assembly should be consistent with the ground coordinate point. Then, both sides of the web are welded at the joint between the inner diaphragm and the lower wing plate. **Figure 11** shows the assembly on the flange plate using wedge in place.

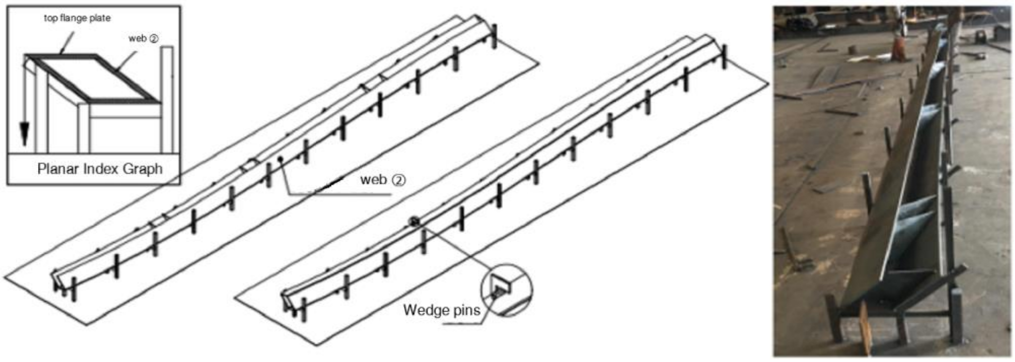

Figure 11. Schematic layout of inner partition

In the sixth step, the welding of the main rod and the secondary rod is carried out after the tire is welded and the welds of the main rod and the secondary rod are polished. The size of the main rod of the two sides of the box type is verified. Following size verification, the simple frame is put into the middle box type secondary rod according to the size of the deepening assembly drawing. The diagonal deviation of the main bars on both sides is controlled between ±3 mm, and the error margin of the T connection between the main bar and the secondary bar should be controlled between ±2 mm. The primary and secondary rod welding schematic diagram and the freeform surface component assembly simulation schematic diagram of are shown in **Figure 12** and **Figure 13**, respectively.

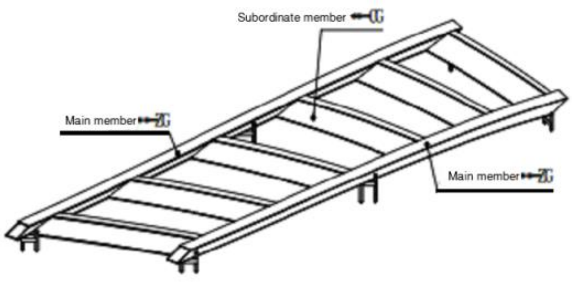

Figure 12. Primary and secondary rod welding schematic diagram

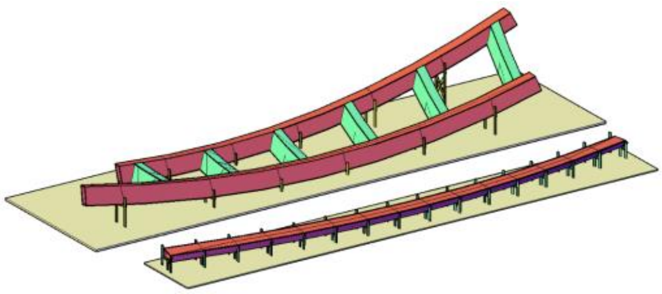

Figure 13. Freeform surface component assembly simulation diagram

5. Flexible docking and welding stress deformation control in the bending-torsion combination unit

5.1. Flexible docking control

After the assembly and welding of a single rod, it needs to be assembled in the factory as squareness. Due to the particularity of the structure and components of this project, there is a slight deviation in the modeling of special bars by the software. The members of this project are all spatial bending and torsion, and the arc of local bending and torsion is large, so it is difficult to control the complete fitting between the arc of the member and the theoretical arc during processing. The stress shrinkage caused by the welding process and ambient temperature during machining will also cause a small deviation of the bar in radian. The section thickness of most members is small, and the members are prone to bump and deformation in the process of loading and transportation. At the same time, deviation will also occur due to gravity during hoisting.

In order to ensure successful rod assembly, 100 mm non-welding is reserved for the main weld of each butt joint end, and site installation and adjustment are reserved. The reserved side is either the end groove side or the non-sealing side, or the end sealing plate is appropriately adjusted depending on the situation.

5.2. Synchronous welding stress deformation control

For the welding of the main weld of the bending-torsion box, two welding machines are used to weld in a symmetrical manner, as shown in **Figure 14**. The detailed welding sequence is as follows: two welders weld the front two welds at the same time until the depth of the two welds is 1/3; the components turn over to weld the opposite two welds 2 until the welding is completed; then, the components are turned over, and the welding of the front two welds 1 is completed.

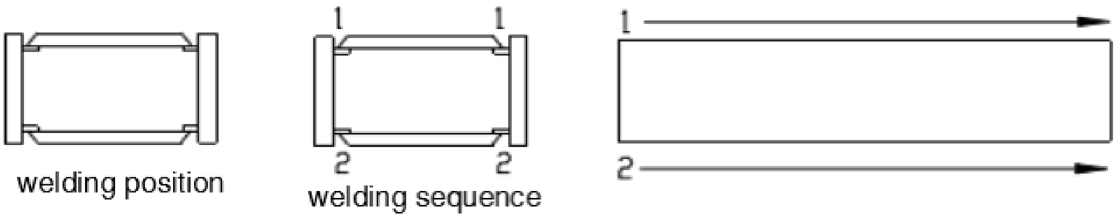

Figure 14. Welding schematic diagram of box components

Since the box panel is thin, and the shape of the component is bending and twisting, in order to ensure a low degree of constraint of the weld after welding, it is necessary to adopt the segmented skip welding technique for the bottom welding of the main weld and the filling welding of the first two layers, as shown in **Figure 15**. The displacement of the entire weld is divided into several segments, with each segment having a length of 800 mm~1500 mm. The welding is then carried out according to the sequence number shown in the **Figure 15**. Each welding length is about 400 mm to 500 mm, and the two sides are synchronized in the same direction.

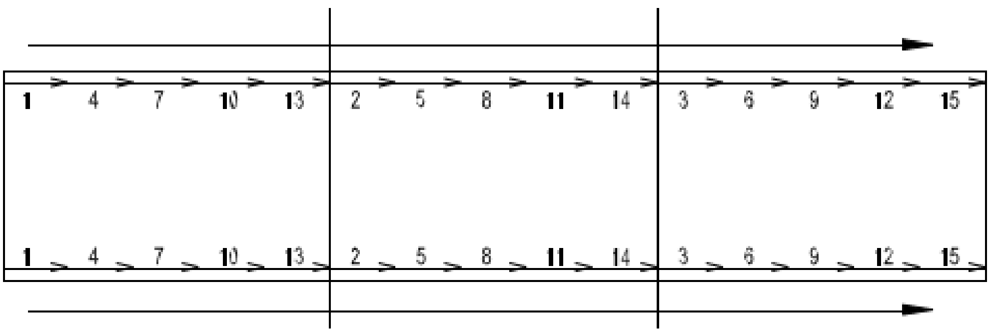

Figure 15. Segmented skip welding schematic

6. Conclusion

In this paper, based on the National Cybersecurity Talent and Innovation Base project and the existing model of the design unit, taking AUTOCAD software as the intermediate platform, the rapid modeling of the construction deepening design model is realized, with a significant improvement in the efficiency of the deepening design. The computer-aided flexible multi-support external support assembly technology, the flexible docking control technology in the bending-torsion combination unit, and the welding stress deformation control technology are all studied and analyzed, which improves the accuracy of freeform surface steel structure construction and provides a reference for similar structure construction.

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Disclosure statement

The authors declare no conflict of interest.

References

[1] Ye C, Lu T, 2019, Design of Super-Long Multi Curved Double-Layer Metal Roof System. Steel Construction (Chinese & English) 34(10): 48–52.

[2] Ma J, Gao Q, Lu T, et al., 2015, Research on Processing Technology and Quality Control of Pipe Component of Ellipsoidal Reticulated Shell. Steel Construction, 30(12): 68–71.

[3] Lu T, Hu Z, Ma C, et al., 2015, Detail Design and Analysis of Ellipsoid Steel Corridor of Wuhan International Expo Center. Construction Technology, 44(17): 1–4 + 17.

[4] Wu WP, Reb J, Li LY, 2011, Simulation Analysis on Spatial Bending and Torsion Steel Structure Erection Procedure of Phoenix International Media Center. Construction Technology, 40(9): 62–64.

[5] Cai YL, Wu J, Ye D, et al., 2016, Construction and Unloading Technology of Bending Structure in Different Planes. Construction Technology, 45(S2): 401–404.

[6] Zhao QK, Shi Z, 2015, Research on the Technology of Spatial Tortile Steel Structure Manufacture. Steel Construction, 30(1): 54–58.

[7] Yang HZ, Chang Z, Yang Z, et al., 2009, Integrated CAD/CAM Information System of Steel Structure for Sun Valley in Expo Axis. Construction Technology, 38(8): 35–37 + 43.

[8] Zhang G, Dong W, Zhao P, et al., 2019, Parametric Modeling and Analysis of Steel Roof Structure of An Exhibition Center. Building Science, 35(11): 1–6.

[9] Zhang S, Yi P, 2015, Research on Parametric Modeling Technique for Special-Shaped Surface Based on Rhino and Grasshopper. Journal of Information Technology in Civil Engineering and Architecture, 7(5): 102–106.

[10] Wang HJ, Qian H, Fan F, et al., 2016, Construction Full-process Analysis for Streamer Space Truss of Hangzhou International Expo Center. Construction Technology, 45(2): 13–17.