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Intelligent Construction Technology of Hyperbolic Curtain Wall

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Abstract: Taking the hyperbolic glass curtain wall project of the Wuhan Jinyinhu Commercial Plaza as an example, the characteristics of different curved glass forming technologies were analyzed in this paper. Combined with the actual engineering situation, the curved steel process is selected to produce the hyperbolic glass curtain wall, and the application of BIM technology in the quality control of hyperbolic glass curtain wall in the production process was analyzed, and the effects of heating condition, bending time, cooling condition, and bending tempering error in the manufacturing accuracy of the curved glass curtain wall were studied, in hope that this project can provide practical reference for similar curtain wall design construction in the future.

Keywords: Hyperbolic curtain wall; Bending process; Building information model; Construction technology

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1. Introduction

With the continuous improvement of productivity and people's living standards in China, the requirements for buildings are no longer limited to their functionality, additionally, the aesthetics and diversity have become an important consideration in architectural design in recent years, and at present more buildings surfaces are designed as curved. Curtain wall, as a conventional decorative wall of modern architecture, it plays an important role in the construction and design of curved buildings. In recent years, many scholars have studied the design and construction technology of the curved curtain wall.

Liu Mengwen et al., [1] combined with Shaowu Sports Center Project, studied the parametric modeling of special-shaped steel structure based on BIM technology, and observed that BIM technology improved the utilization rate of standardized template, and computer numerical control (CNC) machining accuracy of special-shaped components. In addition, Guo et al., [2] simulated the construction process of Fuzhou Olympic Stadium based on BIM technology, and analyzed and studied the difficulties in the application of BIM technology in large-scale gymnasium projects, subsequently summarized the treatment methods when the model in inconsistent with the actual construction plan. Further, Wei Cheng et al., [3] used BIM technology to arrange the actual site during the construction of the gymnasium project of the Beijing Jianzhu University, so that the site layout could meet the requirements of the construction safety, green environmental protection, and construction safety. Pengke et al., [4] studied the application of BIM technology in the construction process of steel roof truss, and concluded that using BIM technology to compare different steel roof construction schemes was beneficial to the optimization of construction methods. Li et al., [5] analyzed the stress distribution of curved glass curtain wall during micro-warping forming process, and results showed that the stress of glass curtain wall bent by reasonable micro-warping

process was less than the allowable value under the wind-seismic load. Su et al., [6] studied the construction technology of hyperbolic aluminum plate curtain wall, and they concluded that, there a was stress concentration at the nodes of hyperbolic curtain wall, and the finite element analysis could be used to optimize the structural nodes. Liu et al., [7] further took the project of the China Maritime Museum as an example, they used the finite element analysis to study the influence of the curtain wall locking network tension scheme on the tension accuracy, and obtained the conclusion that the tension accuracy was the best when using the horizontal and vertical mixed tension construction scheme. Another researcher, Wang Caifeng et al., [8] used three-dimensional scanning technology to reverse the modeling of curved glass curtain wall in construction site, and used BIM technology to control the quality of glass curtain wall cutting and splicing, which improved the accuracy of curtain wall construction. Tong et al., [9] analyzed the application of BIM technology in the construction of the curved curtain wall, and noted that BIM technology can produce considerable value in parametric design of the curtain wall, simulation of a construction process, material management and collision inspection. Lastly Liu et al., [10] studied the three-dimensional lofting technology and plate hoisting technology of curved curtain wall based on the sail tower project of Chongqing Laifushi Square, which provided a solution for the construction difficulties, such as accurate lofting of the irregular curtain wall.

Many literatures have provided theoretical basis and practical experience in the design and the construction of curved curtain wall, however, at present there are on few studies on the intelligent cold bending forming technology of curved glass, and the intelligent processing quality control of curved glass. Taking the hyperbolic curtain wall project of the Wuhan Jinyinhu Commercial Plaza as an example, this paper compares a variety of curved glass forming processes, selects the optimal forming process combined with design requirements and construction conditions, and uses BIM technology to control the quality of the glass intelligent processing machine.

2. Engineering situations

Wuhan Jinyinhu Commercial Plaza, also known as Wanda Plaza is located at the junction of Jinshan Avenue and Huhuan Road in Dongxihu District of Wuhan City, Hubei Province. The total building area is 173,840 square meters, and the main structure is reinforced concrete frame structure. The basement of the plaza is 2 layers, while the ground is 4 layers, and the upper layer is 5.1 meters high, with the total building height is 24 meters. The Plaza project total investment was 1.5 billion, and this plaza is famous for entertainment, shopping, and also as one of the integrated businesses places (**Figure 1**).

Figure 1. Architectural design effect diagram

The project is divided into five facades, the east, south, west, north, and southeast. The curtain wall is, mainly, includes the aluminum plate, glass, and electronic grid screen. The material of the keel structure used in the facade of the curtain wall is a square steel tube, with material Q345B. The cross-section size is mainly 100 * 6,150 * 100 * 8,200 * 10,400 * 200 * 12,300 * 200 * 10,150 * 8, and the total weight is 502 t, meanwhile the maximum cantilever distance of the keel structure is 10 m. Among them, the southeast facade is the projection shape of the steel keel with glass and electronic grid screen. The projection shape and the vertical facade are maintained at a 15-degree inclination angle. To ensure the smoothness of the large surface, the electronic grid screen and glass are designed as hyperbolic shapes, and the glass and grid screen are installed on the steel keel structure through point connectors. The total area of glass is 1,050 square meters, and the total area of the electronic grid screen is 896 square meters as shown in **Figure 2**.

Figure 2. Building south-east corner view

3. Surface glass intelligent forming technology

3.1. Intelligent cold bending forming technology of curved glass

The main principle of curved glass cold bending forming technology is that, within the range of glass elastic deformation, the glass is fixed on the platform by using the fixture, and is bent to shape a design by adjusting the fixture. The specific steps of glass elastic deformation are as follows; (1) A certain number of glass fixtures are used to fix the fixture base on the special processing platform, according to the designed position; (2) The glass which needs to be bent is placed on the platform, the glass edge is clamped and fixed tightly by adjusting the bolt of adjusting fixture; (3) The glass size is reviewed and the bolt is fixed after adjustment; (4) Initial fixing adjustment bolts; (5) Stand the glass for a period of time, after the glass forming, disassemble the fixture; and (5) Glass molding is finished with a cold bending.

3.2. Intelligent hot bending process for surface glass

There are two kinds of glass hot bending process, namely, the hot bending process and bending steel process. In the hot bending process, the glass is heated to near softening point, and through a variety of specific molds, the glass becomes a product with a non-planar shape after natural cooling, therefore it belongs to the non-safe glass type. The forming temperature of hot-bending glass is generally about 580°C, mainly near the softening point of the glass. Therefore, mastering the forming temperature and strict model making method are the key to form a good hot bending glass. The bending and tempering process of the glass to the softening point is made through specific mold and equipment. The glass is rapidly and uniformly cooled by cold air. The surface of the tempered glass is forms uniforms compressive stress, while the internal of

the tempered glass forms tensile stress, which effectively improves the bending and impact resistance of the glass, and the strength is 4 times more that of the ordinary glass. When broken, they split into uniform, no split mouth, which can easily hurt others by small particles, therefore, this glass belongs to the safe glass type. The dimensions processing of curved glass is processed by bending and tempering, and all these processes are conducted based on the three-dimensional data of BIM model. Therefore, the machining accuracy is high, which is very suitable for the surface effect of building appearance. The installation effect of this glass is better than the cold-formed glass curtain wall, however the processing cost of hot-formed glass curtain wall is high, the energy consumption is large, and the production cycle is slow. Cold bending process can be used to produce curved glass with small warpage or deformation, glass size correction, and others, which has a low production cost, small size error, can create more economic benefits, using simple equipment the process, and can easily be operated. However, the cold bending will produce residual stress in glass forming, which may adversely affect the stress in the process of the glass use. For the glass formed by cold bending, in the process of structural calculation, it is important to analyze the residual stress in the glass, and fully consider its influence on the deflection and strength of the glass.

As a large commercial building, the southeast corner intelligent screen project of Jinyin Lake Commercial Plaza in Wuhan East West Lake District has high requirements for the forming effect of the facade. To ensure the uniform and straight seam of the glass panel, the installation accuracy should be controlled at the millimeter level. However, the installation effect of the cold-formed curved surface glass curtain wall could not meet the engineering quality requirements. Meanwhile, some curtain wall glass panels in this project are hyperboloid, which is difficult to process. Hyperboloid modeling makes the radian, size, chord length, and arch height of each glass different at all positions, resulting in the uniqueness of each glass. Only by submitting the size information of each glass plate to the processing plant through BIM model, the processing accuracy of the glass can be ensured in the bending and tempering process. In addition, the residual stress produced by a cold bending process will increase the self-explosion rate in the process of on-site installation and in the subsequent use, and the uniqueness of the glass in this project will greatly increase the duration, the cost, and economic loss. In view of the above reasons, Wuhan East West Lake District Jinyin Lake Commercial Plaza southeast corner of the glass curtain wall selects hyperboloid glass bending process production as a choice.

4. Intelligent machining quality control of curved glass

4.1. Application of BIM technology

The corner of the glass curtain wall at the southeast corner of the Jinyinhu Commercial Plaza in Wuhan East-West Lake District is hyperbolic glass. In order to ensure the machining accuracy of hyperbolic glass, a number of BIM software is used in the whole project, and the control of bending steel construction parameters is emphasized. Variety of BIM software is used, because single software use is often unable to meet the needs of the whole process, especially for the special-shaped hyperboloid structure, and each software advantages is used to convert the data information which is required in different stages, as the essential theoretical basis during the implementation stage. In the process of curtain wall deepening design, the construction information transmission process of this project is as follows; The first step is to establish a complete spatial model of the Wanda Plaza in Rhino software; The second step is to extract the key control lines to computer-aided design (CAD) software; The third step is to import the key line of CAD into x-steel accurate modeling; and the fourth step is the model is returned to CAD after accurate modeling, providing guidance for machining. The rhino model, key control lines, and X-steel model of Jinyinhu Commercial Plaza are shown in **Figure 3**, **Figure 4**, and **Figure 5**.

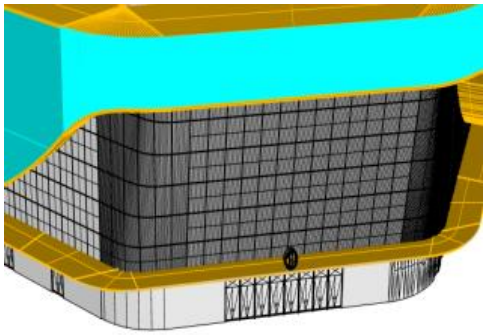

Figure 3. Rhino Model

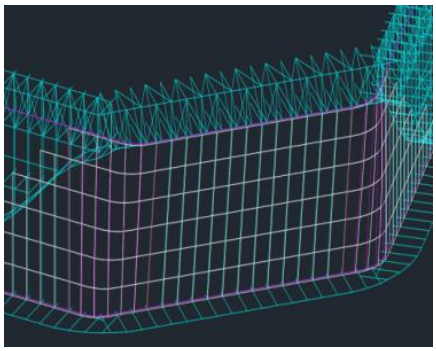

Figure 4. Key control lines

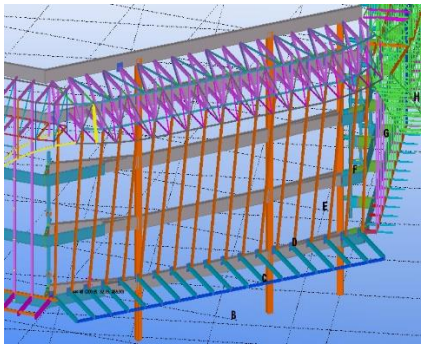

Figure 5. X-steel model

4.2. Construction parameter control of bending steeling

4.2.1. Effects of heating conditions

When the glass is tempered, it must be uniformly heated, otherwise it will cause uneven heating of different parts of the glass, resulting in temperature difference, leading to uneven distribution of the stress, and the possibility of glass burst becomes bigger. Therefore, the heating temperature should not be too high, otherwise, the glass softening phenomenon is sub-heavy, and the viscous flow occurs and deforms. In the process, the vertical is elongated, and the transverse sentence is contracted, which makes the thickness of each part of the glass different, with the thinner part is prone to burst. This situation is mostly occurring at the late cooling stage, and the shape of the debris produced is smaller. In contrast, the heating temperature could not be too low, otherwise the glass does not heat the plastic state, and it can also cause the glass to burst. This situation occurs mostly following few decades of cooling, and the shape of the debris produced is larger.

The heating temperature varies with the thickness of the glass. The bigger the thickness of the glass, the larger is the temperature difference between the surface and the middle of the glass, thereby the stress caused by the burst will be larger as well. Therefore, in general, in the production of curved tempered glass, the tempered temperature of the glass above 12 mm should be ranged from 20°C~30 °C lower than 3 mm ~ 10 mm glass.

4.2.2. Effect of bending time

Glass from the furnace to lose heat. The glass temperature decreases about 30°C/S when the glass temperature is about 680°C, and the room temperature is about 15°C. If the bending time is too long and the heat loss is too much, the glass surface will become hard. When bending, the convex surface of the glass is stretched and broken. In addition, when the furnace glass is bent, the concave surface of the glass is close to the mold. The positive mold is a solid structure, and the outer surface is covered with asbestos paper. The heat exchange between asbestos paper and glass is mainly through heat conduction. Asbestos is a good insulation material, thereby the concave surface of glass dissipates less heat through heat exchange.

The other side of the glass is the convex surface, which contacts with the frame of the negative mold, and most of the surface is exposed to the air, therefore the heat loss of the glass convex surface is more. If the bending time is too long, the temperature difference between the two sides of the glass is larger, and the stress distribution is seriously asymmetric, which can easily cause the burst. Therefore, to control the bending time, generally 3mm ~ 10mm glass bending time is controlled in 2s ~ 3s, more than 12mm glass bending time is controlled in 3s ~ 4s.

4.2.3. Effects of cooling conditions

In the actual production, the wind pressure of the cooling wind grid is generally adjusted to the same. Since the temperature on both sides of the curved glass is different, as mentioned above, the heat loss on the

convex surface of the glass is greater than that on the concave surface. Therefore, asymmetric cooling will inevitably cause uneven glass tempering, and the stress distribution is seriously asymmetric. The tensile stress layer moves to the surface layer, which reduces the internal quality of the tempered glass, subsequently increases the possibility of cracking.

In addition, in the production it is often found that the movement of the cooling air grid is not synchronized, for example, some air nozzles of the air grid are blocked, the glass exceeds the effective blowing area of the air grid, and the glass is not in the middle position in the air grid, and is biased to one side. These will also lead to uneven glass tempering, and increase the risk of bending tempered glass burst.

4.2.4. Adjustment of bending steeling error

To reduce the manufacturing error of bending and tempering process, firstly, after all the coordinate points are derived, the project is compared with the on-site concrete structure, and the space of the connection point between the outside and the glass is kept unchanged. Subsequently, the connection position between the inside of the rod and the concrete is adjusted to ensure that it can be fixed on the embedded parts, ensuring the structural force transmission is safe. At the junction of each curved glass and plane glass, a vertical split glass is reserved as the closure section. When the glass on both sides is installed, the actual processing size of each glass in the closure section is measured based on the actual site, to reduce the error between theoretical analysis and actual construction.

5. Conclusion

Based on the hyperbolic curtain wall project of Wuhan Jinyin Lake Commercial Plaza, this paper analyzed the construction technology of hyperbolic glass curtain wall, and we concluded that the glass bending and tempering process has high machining accuracy, therefore, compared with hot bending and cold bending process, bending and tempering process is more suitable for curved glass curtain wall engineering. In addition, the influence of heating, bending time, cooling and other processes on the production process of curved glass curtain wall is analyzed, and the optimal bending and tempering forming parameters are obtained. Finally, using BIM technology to extract hyperbolic glass curtain wall parameters, improves the overall drawing accuracy, and further provides guidance for processing.

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The authors declare no conflict of interest.

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