Academic Journal of Architecture and Civil Engineering
Print ISSN: 2960-0235
Online ISSN: 2960-0243
DOI: https://doi.org/10.61784/ajace3015

HIGH-PRECISION CONSTRUCTION TECHNIQUES AND APPLICATIONS FOR WOOD-GRAIN TEXTURED EXPOSED CONCRETE COLUMN-FREE SPIRAL STAIRCASES

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Abstract: This paper takes the wood-grain textured fair-faced concrete column-free spiral staircase project at the China Grand Canal Museum as an example, summarizing and presenting its one-time molding construction method. This method utilizes BIM high-precision modeling technology to accurately extract the spatial curve data of the spiral staircase, optimizing the formwork system layout and template splicing scheme to achieve digital construction and ensure high-precision results in a single pour. Furthermore, a steel-wood composite formwork system is employed, using high-strength steel keel support and finely crafted wooden templates for curved surface shaping, guaranteeing the accuracy of the spiral staircase's curves, improving construction efficiency, and ensuring structural stability. Finally, a one-time pouring process is used, employing a layered composite formwork combining pine wood grain panels and fair-faced wood template liners to accurately replicate the texture of natural wood, ensuring a delicate finish after demolding and avoiding the impact of subsequent repairs on the visual quality.
Keywords: Wood-grain texture; Fair-faced concrete; Column-free spiral staircase; One-time molding

1 INTRODUCTION

Fair-faced concrete, as a manifestation of modern architectural style, is cast in a single pour without external decoration.Its natural aesthetic is derived from the texture of the concrete, construction joints and seams, and tie-rod holes [1]. This significantly reduces the materials used in subsequent decoration work such as wood and stone, shortens construction time, and substantially lowers construction costs, demonstrating harmony between man and nature.
The improvement of building standards has placed higher demands on the craftsmanship and aesthetic effects of fair-faced concrete technology. Huang Zhongyi summarized the research status of fair-faced concrete in four aspects: mix design, mechanical properties and durability, workability, and appearance quality[2]. Wei Yu et al. studied the effects of water-soluble organosilicon penetrating protective agents and acrylic film-forming protective agents on the carbonation resistance of fair-faced concrete[3]. Ji Hailin et al. established quantitative parameters for concrete performance to study the mix design of high-durability fair-faced concrete, and combined this with research on the construction technology of thin-walled structures to develop guidance for the preparation and construction of fair-faced concrete in practical applications[4]. Gu Qiongying et al. focused on the application of large-volume, high-strength fair-faced concrete in public spaces at Xiong'an Station, studying key issues such as the application form, beam and column shapes, and spatial effects of fair-faced concrete, and proposed solutions[5]. Wei Yinghong et al., in conjunction with the construction of Xiong'an Station, applied BIM, GIS, intelligent layout, and 3D laser scanning technologies to address project difficulties in areas such as integrated pipelines, irregularly shaped fair-faced concrete areas, and steel structures, establishing a BIM construction application technology system[6]. Niu Shixin discussed the characteristics of fair-faced concrete from the aspects of surface texture and decorative effect, greatly improving the construction effect of fair-faced concrete[7]. Similarly, in the construction of structures such as stairs and walls, Zhang Hongtao et al., by analyzing the technical difficulties in the construction of spiral staircases, innovated key technologies for spiral staircase construction, solving problems such as welding difficulties and installation difficulties between the treads of spiral staircases[8]. Tang Guangxian et al. focused on the key construction points, including the control of the bottom elevation of the stairs, the fabrication and support of stair formwork, the design and erection of full scaffolding, and concrete pouring[9]. The aforementioned studies mainly focus on optimizing parameters such as the mix design and mechanical properties of fair-faced concrete, or using BIM to guide the construction of beams, slabs, and columns. However, there is less research on the construction methods of complex fair-faced concrete structures such as spiral staircases and curved walls. Therefore, this paper takes a wood-grain fair-faced concrete column-free spiral staircase as the research object, and optimizes the key construction technologies affecting the aesthetic results, such as measurement and positioning, component optimization, and formwork reinforcement, to achieve an integrated design of structural performance and decorative effect.

2 PROJECT OVERVIEW

The main structure of the tower of the China Grand Canal Museum project is a frame-shear wall structure, and the

podium exhibition hall is a steel structure system with few walls and large spans, divided into office tower area, museum area, and podium. This project is located at the intersection of axes B13-B14 and BD-BE in the southwest corner of the multi-functional hall on the first floor of the podium.
The staircase spans a height of 6.05m, with a total of 30 steps. The central angle corresponding to each step is 14.45°, and each step is 165mm high. The steps always revolve around the same center, and the bottom shape is a continuous three-dimensional curved surface. The staircase has one platform; the first resting platform is at the 12th step, with a corresponding central angle of 179.39°. The staircase connects to the second floor of the building, has no frame columns, and is a cast-in-place concrete structure. The thickness of the stair slab is 300mm, with a maximum thickness of 715mm in some areas. Fair-faced concrete is used, and the concrete strength grade is C30, see Figure 1.

Figure 1 Effect Drawing of a Wood-grain Fair-faced Concrete Column-free Rotating Staircase

3 CONSTRUCTION CHALLENGES AND DIFFICULTIES

(1) The bottom formwork of the staircase is a continuous three-dimensional curved surface and is circular, making its fabrication and support relatively complex. The inner arc length of the spiral staircase is shorter than the outer arc length, and the inner arc line is steeper than the outer arc line in terms of elevation slope. The staircase bottom slab presents a twisted inclined surface, and the elevation of the staircase bottom slab changes continuously from the inside to the outside along the same radial direction. Controlling the elevation of the entire staircase bottom surface is complex, and the fabrication and support of the bottom formwork are quite challenging.
(2) The height of the staircase bottom formwork changes with the angle around the center, resulting in significant variations in the height of the scaffolding support. The spiral staircase has a double-layer construction section, with a clear space of approximately 4 meters between the two layers, increasing the difficulty of scaffolding erection.
(3) The construction site has a dense arrangement of scaffolding steel pipes, resulting in limited working space for workers during concrete pouring. The entire spiral staircase needs to be poured in one go, making the pouring process quite challenging.

4 CONSTRUCTION PROCESS AND CONTROL POINTS

High-precision construction process for wood-grain exposed concrete column-free spiral staircase: Detailed design → Formwork and keel processing and preparation → Support frame erection and installation → Installation of bottom and outer wood-grain formwork → Installation of tie rods → Rebar tying → Installation of stair tread formwork → Installation of inner and handrail wood-grain formwork → Concrete pouring and curing.

4.1 Detailed Design

Before on-site construction of the exposed concrete formwork, the formwork joints and visible seams are divided according to the designer's requirements to confirm the final wood-grain formwork layout rules and direction. This addresses complex curve problems in advance to ensure one-time molding accuracy. The detailed design includes the following:
(1) Using BIM 3D design software to model the spatial curves of the spiral staircase, extracting detailed geometric information of each part of the staircase, and optimizing the direction and position of the formwork layout. According to the design requirements, the formwork division and joint methods are adjusted to ensure that the size and shape of each formwork meet the construction accuracy.
(2) Clearly defining the layout of formwork joints and visible seams according to the layout principles, especially the joint design of the spiral structure, to reduce the number of joints. Through precise calculations, ensure that the formwork divisions can effectively resist the internal and external pressure during concrete pouring, reducing deformation during construction.

(3) Based on the formwork shape and size, optimize the formwork cutting plan, select appropriate plate thickness and strength to ensure maximum reduction of material waste and enhance the stability and reusability of the formwork.

4.2 Formwork and Keel Processing and Preparation

Based on the data in the BIM model, CNC machine tools are used to cut the formwork and keels. Through CNC cutting technology, every angle and edge of the formwork and keels are precisely cut, and the panels are numbered, with an error control within 1mm. The steel keels are made of 8mm thick steel plates, forming curved steel keels through high-precision cutting and welding processes. For the specific curvature of the staircase, the bending angle is adjusted according to the design requirements to ensure the stability of the keels in both vertical and horizontal directions. This ensures high fidelity reproduction of complex curved surfaces and irregular structures, see Figure 2-3.

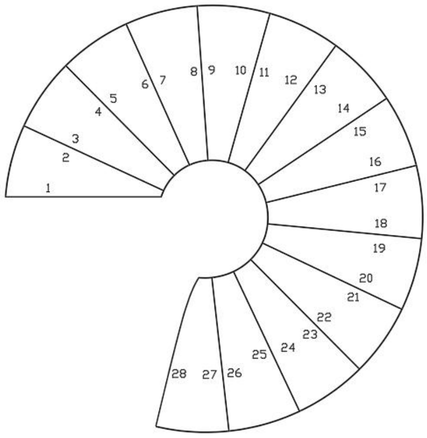

Figure 2 Formwork Decomposition Diagram

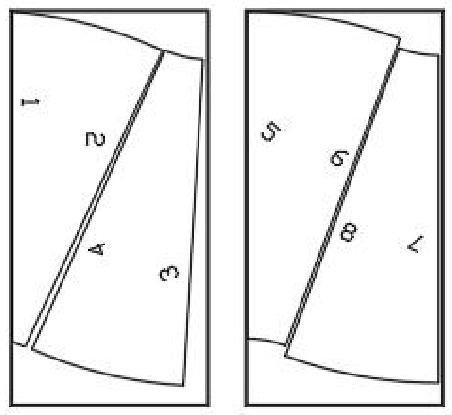

Figure 3 Formwork Preparation Diagram

4.3 Support Structure Erection and Installation

First, lay out the control lines for the inner and outer arcs of the spiral staircase, as well as the control lines for the first-floor steps. Extract the vertical support heights from the model data and mark them on the formwork support layout plan. Based on the formwork support layout plan, arrange the longitudinal and transverse members of the support structure, and erect vertical support members of varying heights at the intersection points. Upon completion, re-verify and inspect the erection heights, see Figure 4.

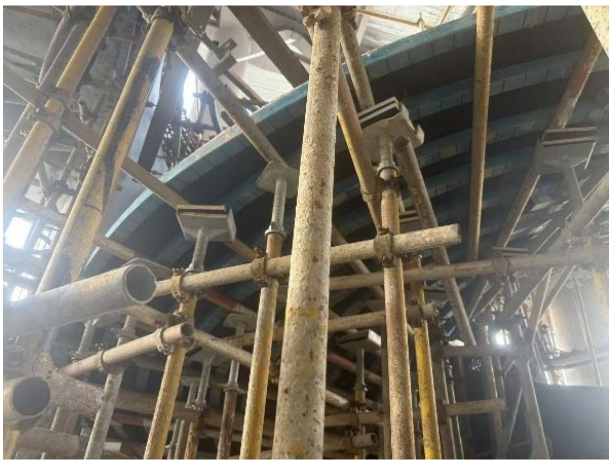

Figure 4 Formwork Support Frame Effect Diagram

4.4 Installation of Bottom and Outer Wood Grain Formwork

The bottom formwork of the spiral staircase uses a main keel of round steel pipes, secondary keels of curved square steel, and laminated composite formwork. The round steel pipes are laid out along the curvature and placed on top of the vertical supports. The curved square steel is placed on the round steel pipes and fixed by electric welding. The outer formwork uses curved steel keels, square steel secondary keels, and laminated composite formwork. The digitally cut steel keels, square steel, and laminated composite formwork are shaped and assembled. The laminated composite formwork consists of a fair-faced wood formwork liner and a wood grain texture panel. The prepared fair-faced wood formwork liners are assembled piece by piece and fixed to the square steel keels with a pneumatic nail gun. The formwork joints are connected with fasteners. Finally, the wood grain texture panels are glued onto the liner, ensuring that the formwork perfectly matches the actual construction curvature, Figure 5-6.

Figure 5 Bottom Formwork Keel Diagram

Figure 6 Bottom Formwork Keel Diagram

4.5 Installation of Tie Rods

According to the design drawings, tie rods are installed on the back of the formwork at specified intervals. Five-section high-strength bolts are used for the tie rods, and the center line of the bolts is aligned with the formwork joints to ensure a tight fit and prevent concrete leakage. The five-section tie rods connect the formwork to the support frame, providing sufficient support to prevent displacement of the formwork during concrete pouring, Figure 7.

Figure 7 Tie Rod Arrangement

4.6 Rebar Tying

During the rebar tying process, the rebars must be tied in the order of their assigned numbers. Prying or bending of the rebars on the work surface is strictly prohibited. Precast concrete spacers of a color similar to the fair-faced concrete should be used. The ends of the tying wires must face inwards towards the rebar, and must not be exposed to the formwork to prevent rusting of the wire ends, which would affect the aesthetic quality of the fair-faced concrete. Five-section tie rods should be used for the fair-faced concrete. When using continuous threaded rods, special plugs should be installed to prevent grout leakage at the bolt holes, see Figures 8-9.

Figure 8 Stair Section Rebar Tying Diagram

Figure 9 Stair Handrail Rebar Tying Diagram

4.7 Installation of Staircase Surface Formwork

During the installation of staircase surface formwork, each formwork panel must be accurately aligned and leveled. Two 150*150mm pouring and vibrating openings should be left every two steps of the staircase. Reinforcement measures should be applied at the joints to ensure stability and prevent formwork displacement or deformation during construction, ensuring consistent and high-precision concrete forming, see Figure 10.

Figure 10 Pouring and Vibrating Opening of the Stair Section Surface

4.8 Installation of Inner Side and Handrail Wood Grain Surface Formwork

The inner side formwork uses curved steel keel + square steel secondary keel + laminated composite formwork. The digitally cut steel keels, square steel, and laminated composite formwork are assembled on the ground as a whole unit, and then lifted into place as a single unit, reducing high-altitude work and improving installation efficiency, see Figure 11.

Special attention should be paid to ensuring that the handrail surface formwork matches the wood grain effect of the staircase design. 200*200mm pouring and vibrating openings are left every 1m on the handrail surface formwork. The joints are sealed to prevent leakage and ensure the final concrete surface quality and accurate wood grain effect, see Figure 12.

Figure 11 Side Formwork Installation

Figure 12 Pouring and Vibrating Opening for the Handrail Surface

4.9 Concrete Pouring, Curing, and Forming

For the column-free spiral staircase structure, a single-pour vibration molding method was used for concrete pouring. Concrete was poured through the designated pouring and vibrating openings and vibrated promptly.

When removing the formwork, hard objects should not directly contact the wall. Formwork or wooden blocks should be placed at the contact points with the wall to avoid damaging the wood grain pattern and corners. When removing the main and secondary formwork, they should not be dropped directly but carefully lowered and stacked by hand before being lifted away. They should not be piled near the wall. After the concrete formwork is removed, natural curing is applied, Figure 13.

Figure 13 Effect Diagram after Formwork Removal

5 BENEFIT ANALYSIS

When using the high-precision construction technique for wood-grain textured fair-faced concrete cantilevered spiral staircases, the resulting wood grain texture is uniform and natural, without joint misalignment or color differences. The overall appearance is excellent, eliminating the need for secondary finishing work. This reduces secondary grinding, repair, and manual wood grain treatment, shortens the construction period, reduces material waste, and lowers hidden costs. Taking a project in Hangzhou as an example, the benefit analysis is as Table 1:

Table 1 Economic Benefit Analysis of a Project in Hangzhou

Method	Item	Quantity (㎡)	Unit Price (yuan/㎡)	Total (yuan)
One-time molded wood-grain fair-faced concrete	Fair-faced wood formwork	460	110	50600
	Pine wood grain panel	460	135	62100
	Five-section tie rod	460	90	41400
	Steel pipe scaffolding	460	150	69000
	Steel keel and square steel pipe secondary keel	460	245	112700
	Fair-faced concrete	460	600	276000
	Total	/	/	611800
Exterior decoration imitation wood grain fair-faced concrete	Ordinary concrete	460	370	170200
	Chiseling	460	56	25760
	Reinforcement bar planting	460	50	23000
	Metal mesh	460	15	6900
	Fair-faced wood formwork	460	110	50600
	Pine wood grain panel	460	135	62100
	Five-section tie rod	460	90	41400
	Steel pipe scaffolding	460	150	69000
	Steel keel and square steel pipe secondary keel	460	245	112700
	Fair-faced pre-mixed concrete	460	1200	552000
	Total	/	/	1113660
Comprehensive benefit	1113660-611800=501860 元			

6 CONCLUSION

Taking the wood-grain-textured fair-faced concrete column-free spiral staircase project at the China Grand Canal Museum as an example, this paper summarizes its one-time molding construction method. This method utilizes BIM high-precision modeling technology to accurately extract the spatial curve data of the spiral staircase, optimize the formwork system layout and template splicing scheme, and achieve digital construction, ensuring high-precision results in a single pour. Furthermore, a steel-wood composite formwork system is employed, using high-strength steel keel support and finely crafted wooden formwork for curved surface shaping, guaranteeing the accuracy of the spiral staircase's curves, improving construction efficiency, and ensuring structural stability. Finally, a one-time pouring process is used, employing a layered composite formwork combining pine wood grain panels and fair-faced wood formwork liners to accurately replicate the texture of natural wood, ensuring a delicate finish after concrete demolding and avoiding the impact of subsequent repairs on the visual quality.

COMPETINGINTERESTS

The authors have no relevant financial or non-financial interests to disclose.

REFERENCES

[1] An Lin, Fu Zhanguo, Han Rui, et al. Considerations on Key Construction Techniques of Fair-faced Concrete. Brick and Tile, 2023(5): 130-132.
[2] Huang Zhongyi. Research Status of Fair-faced Concrete. Value Engineering, 2021, 40(30): 189-191.
[3] Wei Yu, Chen Pang, Zhang Guilin, et al. Influence of Protective Agents on the Carbonation Resistance of Fair-faced Concrete. Journal of Silicate, 2023, 42(1): 85-91.
[4] Ji Hailin, Zhang Meng, Lin Weiwei. Preparation and Construction Technology of Fair-faced Concrete for Thin-walled Structures. Guangdong Building Materials, 2023, 39(5): 99-101.
[5] Gu Qiongying, Zhong Jing, Du Yulin. Research on Key Technologies of Fair-faced Concrete Application in Xiong'an Station. Journal of Railway Engineering, 2022, 39(8): 81-86.
[6] Wei Yinghong, Wu Yadong, Zhang Tianchi. Comprehensive Application of BIM in the Construction of Xiong'an Station Building and Related Projects. Railway Technology Innovation, 2022(4): 69-76.
[7] Niu Shixin. Characteristics of Fair-faced Concrete. Shanxi Architecture, 2015, 41(29): 128-129.
[8] Zhang Hongtao, Ma Honglong, Tao Tiejun. Installation Technology of Large Prefabricated Steel Structure Rotating Staircase. Construction Technology, 2020, 49(8): 74-77.
[9] Tang Guangxian, Xie Jingwei, Deng Zhiheng. Construction Technology of 480° Concrete Rotating Staircase. Building Construction, 2016, 38(9): 1225-1227.