Product Research and Development

Implementation of Intelligent Prefabricated Construction for Pre-stressed T-Beams on Mountainous Highways

Guofang Ju

China Railway Construction Kunlun Investment Group Co., Ltd., Chengdu 610040, Sichuan Province, China
Correspondence: 876177948@qq.com

Abstract: Intelligent bridge assembly is currently one of the key directions for bridge development in China. Different structures and schemes are suitable for urban and mountainous construction requirements. Taking the Tongzi to Xinpu Expressway as the background engineering, this paper systematically organizes the prefabricated construction-related processes and comprehensively introduces of intelligent prefabrication process of prestressed T-beams.

Keywords: prestress; intelligent prefabrication; steel frame; prestress tensioning; grouting

1 Introduction

In 2019, the Central Committee of the Communist Party of China and the State Council issued the "Outline of Building a Strong Transportation Country", which explicitly proposed that China would build a strong transportation country by 2035. It aims to focus on the basic connotation of a strong transportation country, which includes "People Satisfaction, Strong Security, World Class", and the value orientation of "safety, convenience, efficiency, green, and economy". It benchmarks the comprehensive level of transportation development in developed countries and focuses on building "first-class facilities, first-class technology, first-class management, and first-class service" [1,2].

Since the 21st century, intelligence, informatization, sustainability, and long-term durability have been important research and development directions in bridge engineering worldwide. Due to the large number of engineering practices, China has been at the forefront of the world, but it is only a bridge power and not a recognized bridge-strong country. Due to the vast territory, complex climatic and geological conditions, and uneven economic development levels in China, the technical levels of bridge design and construction significantly vary. Many bridges have shown varying degrees of damage after operating for a period of time, which threatens the operational safety and durability of bridge structures. This issue is directly related to the design and construction of bridges. Although the design of bridges in China tends to be conservative and low economy compared to that of foreign bridges, there are many safety and durability problems. One of the more recognized realities is the serious problem of differentiated construction quality. To solve this problem and address the environmental and traffic impacts caused by on-site construction, rapid construction technology has been developed and used earlier by developed countries such as the United States. Developed countries have successively developed a series of industrialized prefabrication and on-site assembly construction technologies and equipment, which significantly improves the speed of bridge construction and greatly reduces the interference of construction processes on the environment and traffic [2,3].

Three major documents were released in 2016, the "Guiding Submissions on Vigorously Developing Prefabricated Buildings", "Submissions on Promoting the Sustainable and Healthy Development of the Construction Industry", and

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"Thirteenth Five-Year Plan for Prefabricated Buildings". Since then, prefabricated construction has become an important lever for China to promote the transformation and upgrade of the construction industry toward industrialization, standardization, and greenization and achieve high-quality development. The Ministry of Transport launched the "Quality Engineering Tackling Action Plan (2018—2020)" in 2018 to perform concentrated tackling actions, including "two zones and three factories" and "improving the quality of prefabricated bridge components". This plan vigorously promoted the research and application of factory construction, standardized construction, and automated control of bridges and provided policy guidance to improve the construction quality of bridges.

Bridge industrial intelligent construction technology includes construction, management, information, Internet of Things, cloud computing, remote sensing control, and many other technologies. According to the current development level of bridge industrial intelligent construction technology, the current research on related technologies mainly focuses on construction technology. However, other technologies are important for promoting intelligent industrial construction, and that is the focus and direction of future development [3-6].

A mature prefabricated construction system should have characteristics such as environmental protection, sustainability, standardized production, controllable quality and cost, and fast construction progress. China is still in the exploration stage of prefabricated construction. The application of prefabricated bridges will encounter many problems in the actual construction process, including the lack of a multi-professional integrated full-category component industrial chain, difficulty in achieving economies of scale, low design integration, the need for secondary designing, high overall cost, and high transportation costs.

Due to technological development, technological matching, human cognition, and policy factors, the current stage of industrial intelligent construction remains at upgrading the traditional cast-in-place mode, i.e., to implement assembly within a certain range and achieve human liberation. Bridge industrial intelligent construction is the development trend and goal of the industry and can promote the industrialization of transportation infrastructure and even the industrialization of the country.

Large-scale, wide-ranging, and economical friendly and medium-span concrete structure bridges are the most widely used bridge forms in China and the main bridge forms in underdeveloped western regions. The application of prefabricated assembly construction technology can improve the product quality, shorten the on-site operation time, and reduce environmental impacts. This approach has become an important development direction for bridge construction in China [7,8]. In addition, promoting the standardized design, industrialized production, and assembly construction is a key support condition for intelligent construction. Under the current national advocacy of environmental protection, green and low-carbon policies, with the current shortage of labor resources in China, promoting economically reasonable and environmentally friendly bridge engineering construction technology in vastly underdeveloped areas of China will inevitably benefit the development and construction of transportation in these areas.

In 2014, the National Transportation and Transportation Work Conference proposed to accelerate the promotion of the "four transportation" development requirements of " comprehensive transportation, smart transportation, green transportation, and safe transportation". In December 2016, the Ministry of Transport issued the "Guiding Submissions on Creating Quality Engineering for Highways and Water Transportation". Based on the principles of the Ministry of Transport's Jiaofa No. 216 document "Guiding Submissions of the Ministry of Transport on Creating Quality Engineering for Highways and Water Transportation", major national infrastructure projects have performed various activities and measures to implement relevant submissions. The main contents include improving the engineering management level, engineering scientific and technological innovation capabilities, engineering quality level, engineering safety guarantee level, engineering green environmental protection level and construction of quality engineering soft power [1,4,9-11].

The Tongzi to Xinpu Expressway is an important part of the highway network in the "Guizhou Province Expressway Network Planning (Densification Planning) Optimization and Adjustment Study". The "Implementation Plan" requires this project to begin in 2018—2020. The implementation of this project is highly important for promoting the construction of Guizhou Province as a demonstration province for building a strong transportation network in the western region, improving the overall highway network structure of the province, accelerating the construction of the "Great Zunyi" metropolitan area, supporting regional industrialization and new urbanization processes, promoting the rapid development of regional tourism, and building a comprehensive modern regional transportation system.

The Tongzi to Xinpu Expressway Section 4 starts from the Shibizi Bridge, passes through Yangchuan Town, Zhengchang Town, and Yongle Town in the Xinpu New Area, and ends near the Lilong Community. It smoothly connects with the Airport Link of the Meishi Expressway on the west bank of the Maoguan River. The starting and ending mileages range from YK49 + 835 to YK71 + 616.588 with a total length of 21.781 km. The main engineering quantities include 14 bridges (4870 m in total), 4 tunnels (2902 m in total), and 52 culverts and passages. The roadbed is 14 km long with an excavation volume of 6.5941 million m^3 (including tunnel excavation) and a filling volume of 4.11393 million m^3. There is 1 service area and 2 interchanges (Zhengchang Interchange and Minqun Interchange). Bridges account for 22.4%, and tunnels account for 13.3%. The proportion of bridges and tunnels along the Tongzi to Xinpu Expressway is large, and there are high construction quality and safety risks. Quality engineering construction is conducive to quality management and the advancement of quality engineering activities on Guizhou expressways.

In the construction process of this project, the "intensification and industrialization" principle was implemented, with a focus on the construction of a centralized concrete mixing plant, the centralized processing and distribution of steel reinforcement in the processing plant, and the centralized manufacture of prefabricated components in the prefabrication yard. The entire line is equipped with 3 centralized concrete mixing plants, 6 centralized processing and distribution steel structure processing plants, 2 T-beam prefabrication component yards, and 1 small prefabrication component yard. This article also focuses on fully utilizing new technologies and equipment, especially the "Four Modernizations"—industrialization, mechanization, specialization, and informatization—to improve the engineering quality and efficiency.

In the standardized construction of the project, the standardized systems of Tongzi-Xinpu Project Company, Guizhou Transportation Construction Engineering Quality Supervision Bureau, and Guizhou Highway Bureau of the Ministry of Transport were compared, and the principle of implementing the highest standard requirements among the three standards was adopted. During the standardized construction process, the refinement of the management of each content is implemented, and the information technology is fully leveraged, especially in combination with BIM technology, to achieve the intelligence of the prefabrication of the prefabricated structure.

2 Intelligent Prefabrication Content and Technical Reserves

2.1 Prefabrication Preparation

2.1.1 Construction Site

A reasonable site to construct prefabricated beam yards should be selected according to the overall construction progress schedule. The prefabricated beam yard should be equipped with supporting facilities according to the overall construction progress plan and construction technology to ensure its production capacity and construction quality.

Prefabricated beam yards should be selected and planned according to the requirements of "industrialization and specialization" with good division of functional areas, layout of site roads, drainage systems, and arrangement of power facilities. Based on the principles of safety, applicability, economic rationality, and environmental protection, the overall planning and reasonable design should be performed. Considering factors such as the route direction of the T-beams in this section, terrain, bridge location distribution, construction schedule arrangement, number of beams, location of concrete mixing plants, geographic transportation, and material supply, measures should be adopted under local conditions to achieve fast prefabrication speed, high quality, small site construction area, and low cost. The layout of each functional area should be reasonable with perfect supporting facilities. The beam production area, storage area, steel bar processing area, concrete mixing plant, and office living area are relatively independent and do not interfere with one another. The T-beam prefabrication yard is enclosed by walls or isolation nets for closed management.

2.1.2 Informatization Management

(1) Video Surveillance System

A video surveillance system was installed in the steel bar processing area, steel frame production area, beam production area, storage area, entrances and exits, and remaining area of the prefabrication yard. The data signals of each major monitoring point are collected and transmitted to the computer in the monitoring room. Through the authorization of the platform management center system, real-time multi-point-to-multi-point monitoring and management of the front-end video points are performed.

(2) Information Management System

Using a special software, data are collected in real time for each prefabricated pedestal, storage area pedestal, and T-beam, and seamless connections are made with intelligent tensioning grouting equipment and intelligent curing equipment. The basic information of each pedestal T-beam (beam number, construction time, tensioning data, curing situation) is input to informatize the management of the entire beam yard. The data reflect the production situation of the entire beam yard on the computer in the main control room.

2.1.3 Intelligent Equipment Configuration

The steel bar processing plant is equipped with intelligent bending centers, automatic bending machines, Computer Numerical Control (CNC) automatic feeding machines for steel bars, and CNC steel bar straightening and cutting machines. T-beam tensioning and grouting use intelligent tensioning machines and a circulating intelligent grouting trolley. The T-beam curing material adopts a fully automatic intelligent spray curing system and intelligent steam curing system. The T-beam formwork adopts the automatic sliding hydraulic integral formwork.

2.2 Prefabricated Information Digital Construction

2.2.1 Building Information Model Establishment

BIM technology is applied to Zhengchang Bridge according to the project engineering situation to create a BIM model, refer to Figure 1.

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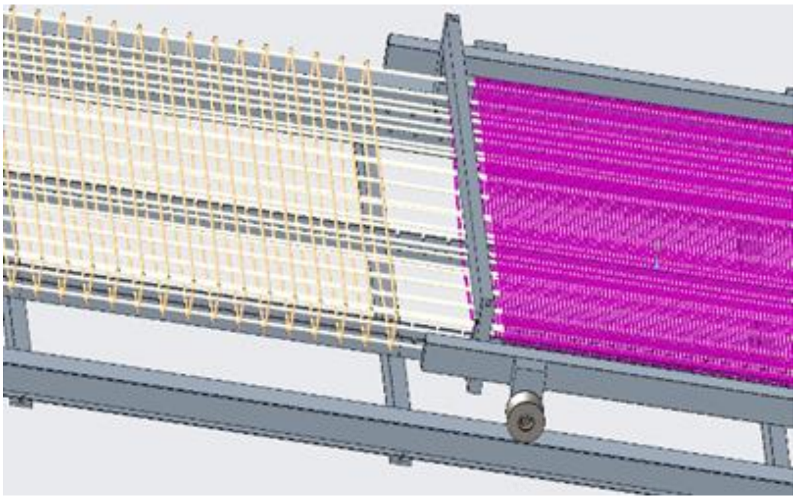

Figure 1 Building Information Model

2.2.2 Construction Deduction and Visual Communication

Using a 4D virtual simulation environment for virtual deduction can intuitively reflect the sequence of each construction process and facilitate visual communication.

2.2.3 BIM and Progress, Quality, Safety Management

Through the BIM and collaborative management platform, the construction progress, quality, and safety are managed, which makes progress management more intuitive, avoids safety risks, and improves the quality control visualization operation [4,12].

2.2.4 Virtual Reality Application System

With the immersion, interaction, and imagination characteristics of virtual reality technology, 3D modeling scenes can be created, and dynamic interaction, artificial intelligence, and intelligent perception can be achieved during standardized construction processes.

2.3 Enhancing the Technological Innovation Capability of Engineering

Taking technological innovation, process innovation, management innovation, and standardized construction as the starting point, the project aims to improve the level of intensive, mechanized, intelligent, and informatized construction control and actively promote the application of "four new" technologies.

2.3.1 Application of New Processes

(1) Infrared Positioning Construction Technology

With the waterproof board hot melt pad laser positioning instrument, infrared positioning (Figure 2) can make the waterproof board hot melt pad accurately positioned and avoid manual positioning, which improves the laying effect of the waterproof board.

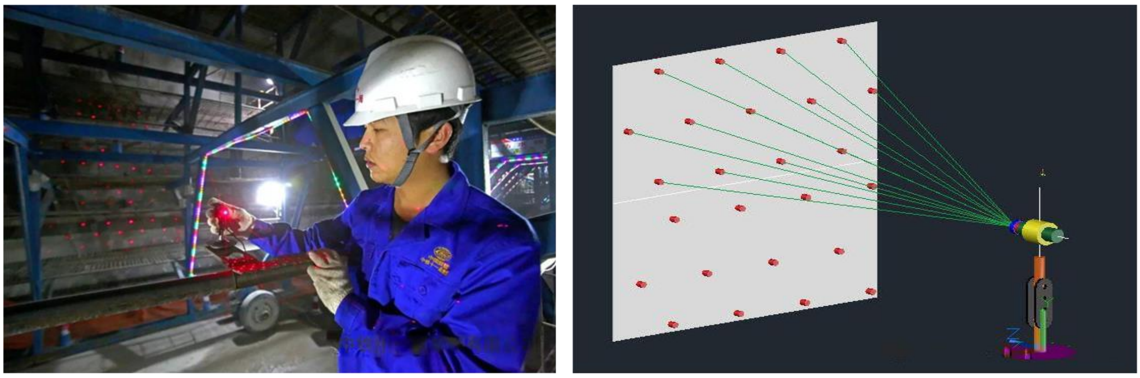

Figure 2 Infrared positioning technology

(2) Ultrasonic Welding Technology for Waterproof Boards

When an ultrasonic welding machine is used, no solvent, adhesive or other auxiliary materials are required, and the cost of use is low. With good safety, ultrasonic welding can be performed immediately after startup, and the welding gun head will not burn the operator under normal situations. Ultrasonic welding saves the preheating waiting time of resistance welding because only 3 seconds is required for a contact point, the production efficiency is high, and no time is wasted for repairing welding holes. The weld has good appearance quality and welding quality, the weld is not damaged, and the waterproof board has good quality.

2.3.2 Application of New Equipment

(1) CNC Steel Bar Sawing Production Line

To product the steel frame and pier main reinforcement threading, a sawing production line is used for semi-finished product processing, which cuts, threads, and grinds the steel bars into a flow production line. This process improves the construction efficiency, reduces the labor intensity, and ensures the threading quality.

(2) Fully Automatic Mat Reinforcement Welding Machine

An automatic welding machine is used for reinforcement processing to automatically process and form mat reinforcement. This automation can avoid quality problems caused by manual welding, such as irregular spacing, unstable welding, and welding damage. The equipment has a fast process speed and saves time and cost.

(3) CNC Steel Processing Equipment

This equipment (Figure 3) adopts a hydraulic system with features such as smooth transmission and high pressure, and it can form channel steel and I-shaped steel in one step. The equipment has a reasonable structure, convenient operation, a strong bearing capacity, a fast process speed, a small size, low energy consumption, high efficiency, no noise, and a long service life.

a) CNC steel bar sawing and cutting b) Fully automatic mat reinforcement welding

Figure 3 CNC processing system

(4) CNC Small Pipe Forming Machine

A small pipe punching machine and a small pipe tip processing machine can automatically punch small pipes according to the drawings, which results in a fast response, high positioning accuracy, low noise, low labor consumption, and low costs. A small pipe tip processing machine is used to automatically process small pipe tips because of its low noise, easy operation, high production, stable performance, smooth processing surface, and lack of scarring. This approach avoids the shortcomings of traditional small pipe welding with low welding quality.

(5) CNC Bending Center and CNC Stirrup Bending Machine

The steel bar bending process is equipped with a CNC bending center and a CNC stirrup bending machine. The CNC bending center solves the bending task of large-diameter and large-profile-size stirrups. The CNC stirrup bending machine solves the bending processing task of small-profile stirrups. The processing precision of semi-finished steel bar is high and the production efficiency is high.

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3 Prestressed T-beam Intelligent Prefabrication

3.1 Beam (T-beam) Process Flowchart

Figure 4 shows the process flow of pre-stressed T-beams, and Table 1 provides the related explanations.

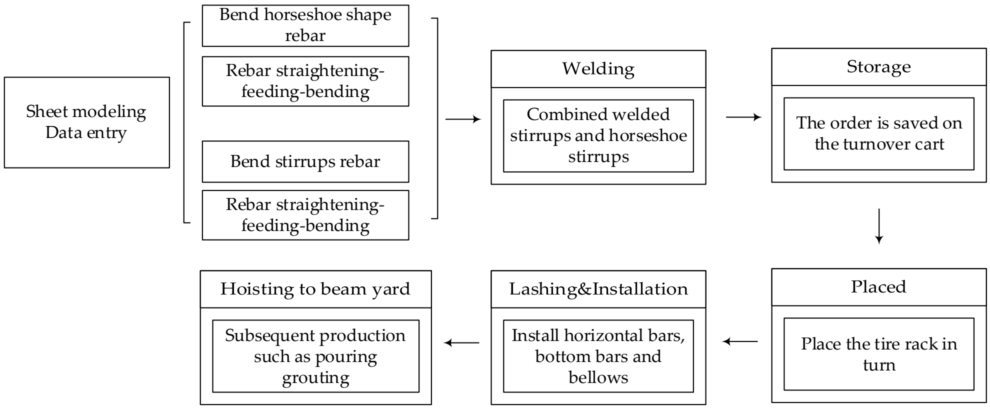

Figure 4 Process flow of pre-stressed T-beams

Table 1 Overall T-beam process flow

Process	Intelligent customized processing	Manual / Capacity production Characteristics	Traditional manual production	Manual / Capacity production Characteristics
Reinforcement Forming	Automatic Straightening and Feeding of Coil Bars	2 workers×10 hours/2 pieces of T-beam web reinforcement; 2 workers×3 hours/2 pieces of T-beam panel reinforcement; Precise bending, strong welding, neat placement, less land occupation, fast turnover and convenient management.	Manual Cutting	6 workers×8 hours/4 pieces of T-beam; Stored according to BOM classification. Batch processing and forming
	Automatic Bending Forming		Semi-automatic Bending Forming with Manual Feeding	
	Automatic Assembly Welding		Batch layout with manual feeding	
Storage and Turnover	Combination parts are stored / turned over in the order of beam sections		Stored according to BOM classification	10 workers×10 hours /2 whole beams; Poor dimensional accuracy, less welding points, slow turnover, more land occupation and inconvenient management.
Web Reinforcement Binding, Welding. Installing Corrugated Pipe	Special equipment placement, ranging positioning, steel bar binding	4 workers×8hours /2 whole beams; Automatic welding and fixing	Manual tying, welding	
Panel Reinforcement Binding, Welding	Special equipment placement, ranging positioning, steel bar binding	4 workers×5hours /2 whole beams; Automatic welding and fixing	/	6 workers×10 hours /2 whole beams
Total	Adding welding equipment, 8-10 workers produce 3 pieces of 40-meter T-beams in one day		22 workers produce2 pieces of beams in one day	
Intelligent robots save 10 workers for web reinforcement processing compared to traditional methods, and 2 workers for panel reinforcement.				

Note: All of the above data are from background engineering project.

3.2 *Intelligent Rebar Processing*

3.2.1 Independent Rebar Processing Plant

An independent rebar processing plant (Figure 5) is set up in the T-beam prefabrication yard, where all rebars in the T-beam are centrally processed. CNC bending center equipment is used for rebar processing to reduce the rebar processing errors.

Figure 5 Rebar processing production line

3.2.2 Selection of Intelligent Equipment

The centralized rebar processing plant (Figure 6) is equipped with intelligent bending centers, automatic bending machines, CNC rebar cutting machines, and CNC rebar straightening and cutting machines to ensure accurate rebar cutting and production dimensions and to reduce human operational errors [11].

a) Rebar cutting b) Automated welding assembly

Figure 6 Rebar forming assembly

3.2.3 Material Classification Management

All raw materials and semi-finished rebars are stored in classified storage areas. Pedestals (≧20 cm) are set up below the storage areas, and the corresponding identification cards (inspection status, usage location, design dimensions, quantity, etc.) are affixed.

3.3 *Rebar Framework Production*

(1) Setting up mobile rebar framework processing sheds, where rebar framework production is performed, improving the construction environment and

ensuring construction is not affected by weather conditions to ensure the production capacity of the beam yard. Secondary leakage protection welding is installed on all welding machines, and CO_2 gas shielded welding is used during welding to ensure processing safety and quality.

(2) The binding construction of T-beam flange rebars and web rebars is entirely performed on positioning frames to ensure that the rebar spacing and alignment meet the design and code requirements. Diaphragm plate rebar installation is performed using positioning frames to ensure consistency in height, spacing, and compliance with design requirements, without any missing rebar. Rebar combing grooves (slots) are strictly set up according to the design requirements of the positioning frame. After the construction on the positioning frame has been completed, the entire assembly is hoisted.

(3) Prefabricate and install negative bending moment anchorage block rebars of T-beams. Those that do not affect the installation of negative-bending-moment corrugated pipes and flange rebars can be prefabricated, spot welded in place, and hoisted to ensure the rebar construction quality.

(4) Control the rebar cover thickness: Special modules are used to produce an equal-strength protective layer cushion block according to the design thickness of the protective layer. Concrete cushion blocks are placed at the bottom and outer sides of the rebar framework, with longitudinal and transverse spacings not exceeding 0.8 m and 0.5 m, respectively. The blocks are arranged in a staggered pattern such as a plum blossom to ensure a clean protective layer for the rebars and prevent exposed rebars. The pass rate of the protective layer thickness should be above 90%.

(5) Installation of prestressed pipes:

Prestressed pipes are corrugated pipes. According to the design documents, the positions of the corrugated pipes and anchor plates are accurately fixed. The spacing and length of the corrugated pipe positioning bars are not less than the code requirements, and the joints are tightly wrapped with plastic tape to ensure no grouting leakage.

Installation and position of the corrugated pipe: fix the corrugated pipe by using positioning frames, the spacing of the positioning frame is 50 cm, set it according to the coordinates of the corrugated pipe provided by the design, and then install and fix the corrugated pipe.

The corrugated pipes are longitudinally extended using one-size larger corrugated pipes as joint pipes with a length of 30-50 cm. Both ends are tightly wrapped with tape to prevent grout leakage. After the corrugated pipes have been positioned and fixed, plastic lining pipes are inserted to prevent the cement slurry from leaking into the corrugated pipes and deforming them.

A length of 5-10 cm is reserved for the end part of the prestressed corrugated pipes, which should be neither too long nor too short, and the pipes should be wrapped and sealed to protect the connection before the beam has been hoisted. When installing anchor plates, the grouting holes should face downward, the vent holes should face upward, and foam adhesive should be used to plug the holes to prevent cement slurry from flowing in and blocking the holes. The concrete near the anchor plates should be compacted to ensure density. Before pouring concrete, all prestressed corrugated pipes should be lined with full-length inner pipes to prevent grout leakage during concrete pouring and subsequent blockages.

(6) Installation of bottom-embedded steel plates: Adjustable nuts are set at the base to adjust the slope of the embedded steel plates according to the longitudinal slope requirements of the design.

3.4 Concrete Pouring and Curing

3.4.1 Selection of Composite Stainless Steel Plates

(1) Use of composite stainless steel for pedestal panels

Composite stainless-steel plates (6 mm thick) are used as pedestal panels for all prefabricated pedestals at the beam yard to ensure the appearance quality of the beams (Figure 7). The prefabricated pedestals are set with an anti-arch according to the pre-camber design.

a) Composite stainless-steel plates

b) Plasma cutting of embedded steel plates

Figure 7 Steel plate processing

(2) Selection of composite stainless steel plates for side formwork

Steel formwork is used for the beam side formwork, where composite stainless-steel plates with a thickness of at least 6 mm are used. The design should be structurally reasonable, easy to assemble and disassemble, and have sufficient strength, rigidity, and stability. The steel formwork is processed and manufactured by a professional manufacturer, and dedicated workers are responsible for inspecting the quality of the formwork processing. After processing and manufacturing have been completed, trial assembly and delivery inspection are conducted at the factory to ensure that the strength, rigidity, material, flatness, smoothness, connection fittings, and dimensions satisfy the design requirements.

For the beam flange formwork with changes in slope, screws and screw rods should be set to ensure that slope adjustments can be made according to design requirements, and the slope remains smooth after hoisting.

Before installing the rebars and pouring the concrete, all prefabricated pedestals and T-beam formwork should be rid of rust, polished, and coated with a special demolding agent. After the demolding agent has been applied, the sample should be immediately covered with a plastic film to prevent secondary pollution. Special demolding agents should be applied to all formwork, and the use of waste engine oil for coating is strictly prohibited to obtain as-cast-finish concrete and ensure the appearance of the beams.

3.4.2 Selection of the Automatic Sliding Hydraulic Integral Formwork

The T-beam formwork adopts automatic sliding hydraulic integral formwork, which can achieve integral formwork sliding, closing, and demolding through the walking system and hydraulic system (Figure 8). Thus, the production efficiency is improved, and finished product damage due to mechanical demolding is reduced.

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Figure 8 Automatic sliding hydraulic integral formwork

3.4.3 Concrete Pouring

The concrete mix ratio is designed based on the grade of the T-beam concrete, selected aggregate, admixtures, and cement grade. Multiple groups are compared. The strength and modulus of elasticity requirements are satisfied, and successful concrete pouring and appearance quality are ensured. One group with a smooth surface and uniform color is selected as the concrete construction mix ratio.

To ensure the strength and workability of the concrete, after the concrete has been produced at the mixing plant, it is transported by concrete mixer trucks and poured through hoppers. Before pouring concrete, it is necessary to strictly inspect the embedded parts of auxiliary facilities, such as the expansion joints, guardrails, drainage pipes, and supports, to ensure completeness. During pouring, it is essential to ensure the accurate positioning of prestressed pipes and reinforcements. Within 2 meters range at the beam end and below the anchor, where the stress is high and the reinforcements are dense, the concrete should be fully vibrated to ensure its construction quality. The pouring of beam concrete adopts diagonal segmentation, horizontal layering, and one-time pouring without construction joints. Observations during construction should be strengthened to prevent grout leakage, under-vibration, and leakage-vibration. Vibrators should be used with insertion and attached types to ensure compactness while avoiding collisions with the prestressed pipes, embedded parts, or formworks. After pouring, concrete sampling should be conducted on-site to make synchronous curing test specimens (2 sets), followed by preloading according to the design requirements to guide the T-beam tensioning construction.

3.4.4 Intelligent Curing of T-beams

(1) Normal temperature curing

For normal temperature curing, high-level water tanks (boxes) are prior choice for automatic sprinkler curing at the beam yard, and pressurized pumps are added when necessary. Sewage from prefabrication yards should be centrally discharged, and sedimentation tanks, filtration tanks, and a circulating water curing system are established. Non-direct discharge of wastewater and sewage from the station is strictly prohibited. Nonwoven fabric covering and automatic sprinkler curing are used for T-beam concrete in the spring and autumn; expandable sunshades and fully automatic intelligent sprinkler curing systems are used in the summer. An intelligent sprinkler curing system, which is controlled by a control cabinet, solenoid valves, buried telescopic nozzles, and pipelines, can achieve the integrated intelligent control of beam yard pedestals [9].

(2) Winter curing

For winter curing, when the temperature is below 5 °C, insulation curing measures are applied. Mobile steam curing sheds and standard curing rooms are set up and equipped with intelligent steam generators for automatic steam curing based on the preset temperature and humidity (Figure 9).

Figure 9 Intelligent curing system

3.5 T-beam Tensioning and Grouting

3.5.1 Experimental Section

To ensure the quality of beam grouting, a grouting test section is set up before the formal T-beam production. The grouting test section is reasonably arranged according to the characteristics of prestressed pipelines in this project, where the grouting equipment and processes are identical to those of subsequent formal grouting work. After grouting has been completed, inspection is performed to verify whether the grouting equipment and construction process satisfy the requirements before the formal T-beam prefabrication can proceed.

3.5.2 Process Inspection

During construction, the frequency of physical inspections is adjusted according to the actual progress, including the thickness inspection of completed concrete protective layers, prestress testing, and grouting compactness testing. All anomalies should be promptly analyzed to identify the essential reasons and ensure product quality.

3.5.3 Intelligent Tensioning

(1) Prestressing strands cutting and threading

Prestressing strands are accurately cut based on factors such as the length of the designed T-beam ducts or pedestals, thickness of the anchorages, length of the jacks, cold stretch length, elastic shrinkage value, elongation value, and working length. Strands are bundled and integrally threaded to avoid disturbance caused by single strand threading. Each batch of strands must undergo the modulus of elasticity calculation and inspection. The use of electric welding machine or flame cutting is strictly avoided, cold cutting is required, and the strands must be independently stored with proper protection measures.

(2) Prestress Strands Tensioning:

Intelligent CNC tensioning equipment (Figure 10) is used for prestressing strand tensioning, where the jacks use a through-hole design. The rated load of jacks should be 1.5 times the design tension force and at least 1.2 times. The jacks should be

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overhauled, partially replaced, and recalibrated after 6 months of use or 300 tensioning cycles. Anchors and wedges must be inspected and qualified before use.

The concrete age of the prefabricated T-beam is not less than 7 days, and after the cubic strength of the test block under the same curing condition reaches 90% of the designed grade of the concrete strength, or meets the design requirements, the prestressed tendons can be tensioned.

The tension force and elongation of prestressed tendons should be controlled. When the tension force reaches the design value, the error between actual elongation and theoretical elongation should be within 6%. The actual elongation is adjusted for the non-elastic deformation of the strands, and the tension force is precisely calculated based on the modulus of elasticity of each batch.

The exposed length after the prestressed tendons have been anchored should be at least 30 mm, and end sealing concrete protection is required for anchorage. For long-term exposure, anti-corrosion measures should be taken. After the anchoring has been completed and inspected, excess prestressing tendons can be cut. Arc welding is strictly prohibited for cutting, and it is advisable to use a sand wheel machine to cut, and at the same time, the anchor must not be damaged.

Figure 10 Intelligent tensioning equipment

3.5.4 Intelligent Grouting

Grouting must be completed within 48 hours after tensioning to prevent prestress loss and wire corrosion. Special grouting materials with strengths that satisfy the design requirements and are determined through tests are used. Before grouting, corrugated pipes should be thoroughly cleaned of harmful materials if necessary if it is stuck to the inner walls. Neutral detergents or soap solutions, which are known not to corrode tendons and pipes can be used for washing, flushing with water and blowing out all accumulated water with oil-free compressed air. The grouting equipment must be cleaned with no residue or water after cleaning [10,13].

Vacuum-assisted grouting was used for T-beam grouting with a circulating intelligent grouting trolley for grouting. The instruments and equipment must satisfy the design specifications to ensure the grouting quality.

During grouting, pressure is applied from the lowest point of the curved and vertical ducts. For ducts arranged in layers in structures, grouting should continuously proceed from bottom to top for each pipe without interruption. All of the highest vent holes should be sequentially opened and closed to ensure smooth air exhaust from the ducts.

After grouting, the anchors should be timely sealed and protected according to the design requirements. For anchorages that require, concrete around the beam end should be chipped and cleaned, and a mat reinforcement should be set to pour sealing concrete. Sealing concrete should have the same strength as the structure or component with strict control of the length of the beam body after sealing. For long-term exposed anchorages, anti-rust measures should be taken. T-beams can be only transported and hoisted after the strength reaches the design requirements.

Figure 11 Arrangement of continuous grouting

4 Intelligent Prefabrication and Benefit Analysis

4.1 Beam Intelligent Manufacturing System Equipment

Table 2 Beam intelligent manufacturing system equipment

<table>
<tr><th>Position</th><th>Equipment</th><th>Advantages</th><th>Labor consumption</th><th>Time consumption</th></tr>
<tr><td rowspan="6">Web plate reinforcement</td><td>Steel bar forming center: 2 sets</td><td>According to the drawing to process horseshoe reinforcement and Web plate reinforcement.</td><td rowspan="3">2 workers</td><td rowspan="7">5 hours</td></tr>
<tr><td>Welding center: 2 sets</td><td>To weld horseshoe reinforcement and web plate reinforcement.</td></tr>
<tr><td>Transfer car: 6 units</td><td>To store welded reinforcement
(2 cars can store 1 beam material).</td></tr>
<tr><td>Web plate frame: 1 unit</td><td>To place welded semi-finished reinforcements one by one, with a fixed spacing.</td><td rowspan="3">4 workers</td></tr>
<tr><td>Assembly center</td><td>Welding of horizontal reinforcement and corrugated pipe positioning bars, more secure and precise than binding.</td></tr>
<tr><td>Small bending machine</td><td>Processing of horizontal reinforcement and corrugated pipe positioning bars.</td></tr>
<tr><td>Bottom reinforcement</td><td>Cutting, bending, welding, and feeding</td><td>Bottom reinforcement cutting, bending, intelligent welding, feeding through horseshoe reinforcement.</td><td>2 workers</td></tr>
<tr><td>Panel reinforcement:</td><td>Assembly center</td><td>After processing with steel bar forming center, transfer to panel frame for intelligent welding.</td><td>4 workers</td><td>1.5 hours</td></tr>
</table>

4.2 Comparison between Intelligent Prefabrication and Traditional Processes

Table 3 Comparison between intelligent prefabrication and traditional processes

Item	Traditional process	New process	Advantages of comparison
Raw materials	Purchase fixed-length straight reinforcement, cut to size as needed, and bend in the production center.	Purchase coil threaded steel bars, straighten and produce in the forming center.	The new process integrates straightening and bending production, eliminates manual cutting processes, improves efficiency, and reduces waste.
Bending production	Manual production according to the BOM of the workpiece, low production accuracy, especially for continuous BOM workpiece production unable to meet design requirements.	Automatically bend and weld combined fixtures in sequence by beam units.	1) The new process automatically produces according to the beam unit, with high precision, and can perfectly realize continuous changes in workpieces. 2) High safety in automatic production, standardized and stable workpiece quality. 3) No manual involvement in production, high safety.
Storage and picking	Stored and stocked according to the BOM of the workpiece, picked out according to the BOM before assembly.	Stored on carts in beam units in assembly order, directly picked from carts before assembly.	New process eliminates cumbersome BOM storage management and picking operations before beam assembly, improves efficiency, and reduces the error of storage and picking operation.
Assembly	New process eliminates cumbersome BOM storage management and picking operations before beam assembly, improves efficiency, and reduces the error of storage and picking operation.	Beam units are picked from carts in sequence for horseshoe ribs and stirrups welding and assembly, with horizontal and vertical robotic arm positioning and fixing followed by binding or automatic welding of horizontal bars.	New process eliminates picking processes, and using robotic arms, automatically completes rebar spacing, horizontal rebar fixing, and welding, making assembly efficient, standardized, and stable in quality, while also greatly reducing the number of workers and workload.
Production management	Offline manual management	Cloud-based management system online integrated management. 1) The project department issues production plans and tasks in the cloud, and the construction party converts production tasks into production documents for production and assembly at the beam intelligent manufacturing center, and the supervisor directly submits the corresponding quality reports to the cloud. 2) Owners, supervisors, project departments, and construction parties can all view the progress of production plans and tasks, quality reports, and other contents in real time.	Production equipment and systems, owners, supervisors, project departments, and construction parties' daily management is unified on the cloud management system, connecting workers and equipment, realizing production automation, and process management, greatly improving management quality and efficiency.

4.3 Key Quality Comparison between Intelligent Prefabrication and Traditional Processes

Table 4 Key quality comparison between traditional processes and new process

Item	Traditional process	New process
Spacing Shape Firmness	The spacing is not uniform, the shape is irregular, and it is easy to loosen during binding. The qualification rates of the two indicators of spacing and protective layer thickness are low.	Standard spacing, consistent shape and drawing, using welding technology, firm and reliable, qualification rate for both spacing and protection layer thickness can reach 99%, with very small differences.
Gradient Effect	Gradually changing at intervals of several workpieces, it is impossible to achieve consistency between the design drawings from theory to practice.	Using single gradients, achieving consistency between theoretical and actual designs.
Precision of Corrugated Pipe Positioning	Manual measurement, large deviations in height/width/shape/positioning, disadvantages: in the later stage, the installation of prestressed tendons is difficult or even impossible to complete.	Laser positioning and marking directly during welding, no need for remeasurement afterward, construction according to position, high precision in height/width/shape/positioning, advantages: producing corrugated pipe curves exactly according to design curve drawings, facilitating prestressed tendons installation, truly reflecting design intention.

4.4 Investment Return Comparison

Table 5 Investment return comparison between traditional and new processes (Unit: CNY)

Investment	Traditional process	New process	Comparison of returns
Equipment Fee	350,000 yuan	4 million yuan	-3.65 million yuan
Electricity Fee	200 yuan per beam	300 yuan per beam	-250,000 yuan
Labor Cost	About 6,760 yuan per beam	About 2,800 yuan per beam	producing 2,500 beams can save labor costs of 9.9 million yuan
Worker Configuration	Rebar production, web plate binding, top plate binding, and main rebar installation a total of 20 workers are needed.	Web plate production requires 5 workers; top plate production requires 3 workers; a total of 8 workers are needed.	Saves 12 workers

Note: Based on an investment of 4 million yuan, calculated over 5 years for 2,500 beams of 40-meter T-beams, savings of 6 million yuan can be achieved.

5 Conclusions

Compared with traditional prefabricated production processes, the new intelligent prefabrication process has the following advantages:

(1) Processing is conducted using system integration, multi-process combination, and standard process control; factory customization and assembly-line operations are used for site management.

(2) Modeling based on design drawings was performed, and standard digital models were established to proactively avoid issues. The molding size accuracy and welding accuracy were 1 mm. The rebar spacing and the thickness of protective layer meet the standard rate of more than 99%. The positioning error of the curved prestressed tendons satisfied the design requirements.

(3) Replace the heavy manual production with automated equipment, systematize the traditional fragmented production processes, and industrialize the construction site; help the owners, supervision unit, and construction unit establish

information-based management system. The intelligent beam yard has high efficiency and low labor cost, which can save more than 60% of the labor cost; the production is safe, stable and reliable, without the need for skilled employees; the steel loss is less than 1%, lower than the existing loss standard of 5%.

(4) Compared with traditional processes, the new process based on a beam smart manufacturing center is safe, standardized, and efficient. It has achieved the original design intention and goal of saving time, effort and money.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Ju, upon reasonable request.

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AUTHOR BIOGRAPHIES

Guofang Ju

Born in July 1983. M.E. Senior Engineer. Work at China Railway Construction Kunlun Investment Group Co., Ltd.

Research Direction: Bridge Construction Management

Email: 876177948@qq.com