Digital Virtual Assembly Technology for Complex Steel Truss Arch Spatial Structures

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Abstract. Due to the fully prefabricated nature of the project's steel truss, high precision control is required during installation. The existing BIM technology cannot account for the production and assembly errors of prefabricated components. A refined BIM+3D laser scanning method is proposed for steel bridges to reduce costs from assembly failures due to poor production accuracy. After the completion of prefabricated component processing and production, precision inspection and virtual assembly can be carried out, effectively avoiding cost waste caused by insufficient precision. By using a customized virtual assembly platform for virtual assembly and combining it with the virtual assembly of actual steel component errors, precise installation support is provided for the complex truss structure of the bridge.

Keywords: Bridge Engineering; intelligent virtual pre-assembly; BIM technology; 3D laser scanning technology; point cloud data

1 Introduction

With the growth of comprehensive national strength and the progress of transportation industry, China's bridge construction level is constantly advancing. In recent years, with the emergence of new bridge materials, structures, equipment and technologies, the construction technology of long-span bridges in China has been comprehensively enhanced. Prefabricated construction methods are often adopted for steel truss arch bridges with complex structures. [1]Traditional detection methods like total stations and feeler gauges are time-consuming, labor-intensive, have limitations and human errors, and are difficult to meet the requirements of geometric quality detection in terms of efficiency and comprehensiveness, thus affecting the forming quality of subsequent structures[2]. After component processing, physical pre-assembly is required, which takes up a large area, has high jig frame cost and consumes a lot of manpower.

With the development of digitalization, non-contact methods represented by three-dimensional laser scanning and intelligent construction methods based on BIM technology become possible solutions. Three-dimensional laser scanning technology, based

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on the principle of laser ranging, can quickly obtain three-dimensional point cloud data of the measured object, being efficient, fast and easy to operate. BIM technology, a multi-dimensional model information integration technology covering geometric, physical and spatial information throughout the project cycle, can achieve the goals of improving work efficiency and quality and reducing errors and risks.

Although the virtual assembly method based on laser scanning and BIM technology has been successfully used in regular buildings, it is less applied in complex steel truss arch bridge structures of long-span bridges. Such structures have a large number of splicing units, are heavy and mostly complex spatial structures, and there are problems such as insufficient space for physical pre-assembly[2]. Therefore, it is necessary to study the virtual assembly technology for long-span bridge steel truss arch structures.

2 Project Overview

The main bridge of the Qingshuitang Bridge is a central-supported steel truss arch bridge, with a span arrangement of 100+408+100m and a side span ratio of 1/4. The upper deck width is 31.0m, while the lower deck is for pedestrians and non-motorized vehicles, with a width of 10.5m. Both the main span and side span lower chord arch axes are second-order parabolas, with a main span rise of 89.914m and a rise-span ratio of 1/4.538. The upper chord arch axis of the main span adopts a second-order parabola tangent to a circular curve for the side span, with a rise-span ratio controlled at 1/5.038 for the upper chord parabola, and a radius of 494.348m for the circular curve of the side span upper chord. As shown in Fig 1.

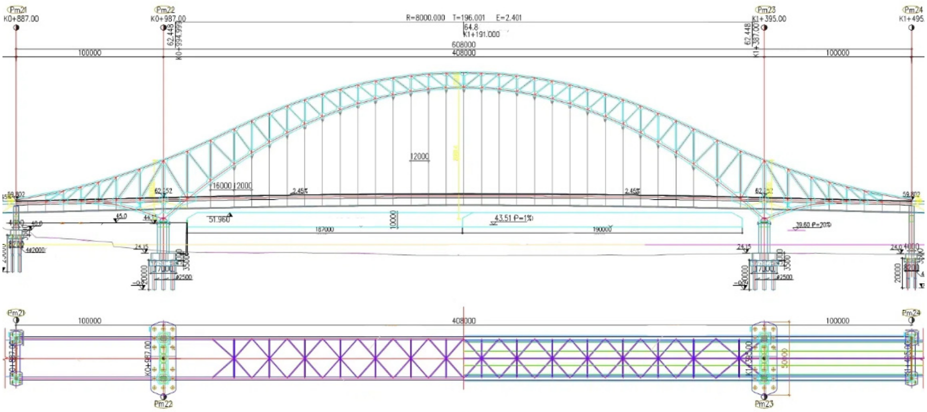


Fig. 1. Elevation and plan view of the Qingshuitang Bridge

3 Challenges in the Construction of Complex Steel Truss Arches

The Zhuzhou Qingshuitang Bridge is a central-supported double-deck steel truss arch bridge, with the steel truss composed of upper and lower chords, web members, and bracing. The main truss arch rib bracing is arranged in the mid-span, with full coverage arrangement for the upper chord bracing at mid-span and the lower chord bracing extending to the first suspension cable. Due to the angle between adjacent segments, the flat connecting node plates are transitioned using a bending method. A truss-type transverse link is set up every two segments, located at the midpoint of the upper and lower longitudinal cross-bracing, with integral node plate bolted connections between the main truss members.

Due to the high precision requirements for the fabrication and connection of steel truss members in the Qingshuitang Bridge, any issues arising from on-site component production accuracy checks and solid pre-assembly of components can lead to construction delays, rework, and wastage of manpower and resources[3]. A solution based on BIM (Building Information Modeling) + 3D laser scanning virtual assembly technology has been proposed to address the manufacturing challenges posed by the differences in precision of steel box girders and nodes. The BIM model of some segments is shown in the Fig 2.

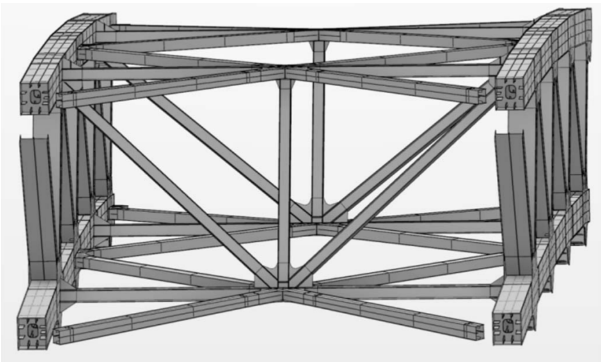


Fig. 2. Segmented BIM model of the steel truss arch

4 Application Process of 3D Laser Scanning Technology in the Project

Traditional methods such as manual measurement and lofting have low cost but low accuracy and low efficiency. Two-dimensional drawings have high industry familiarity but lack a sense of three-dimensionality and are not updated in a timely manner. In digital methods, total station measurement has high accuracy but is slow and has a large workload. Photogrammetry can quickly obtain image data but its accuracy is affected by shooting conditions and data processing is complex. The advantages of the BIM +

3D laser scanning method are high-precision three-dimensional modeling, real-time monitoring and comparison, efficient design change management, improved collaboration efficiency, and data can be saved and reused for a long time. Project personnel have applied it in the Qingshuitang Bridge project.

4.1 Digitization of Members Considering Machining Errors

Three-dimensional laser scanning is a technology that utilizes the principle of laser ranging to record a large number of densely spaced points on the surface of the object being measured, along with their three-dimensional coordinates, re-flectance, texture, and other information. This technology enables the rapid re-construction of a three-dimensional model of the target object, as well as various graphic data such as lines, surfaces, and volumes. The dense point data obtained through this process is also referred to as "point cloud" data.

Using a 3D laser scanner allows for the acquisition of the actual and real structure of truss members with millimeter-level accuracy, enabling the precise reconstruction of the structural components. The scanning process is also fast, with data for a single station typically requiring only 5-8 minutes, significantly enhancing data collection efficiency. The digital scanning process using a 3D laser scanner as shown in Fig 3 typically involves:

（1） Establishing a scanning route: Determining the positions of measurement stations based on the site environment and terrain, maintaining an evenly distributed distance between measurement stations and forming a closed-loop route.

（2） Setting up control points: Selecting some distinctive points on the truss members, such as corners, centers, etc., as control points, marking their positions, measuring their three-dimensional coordinates, and using them as reference control points during data processing.

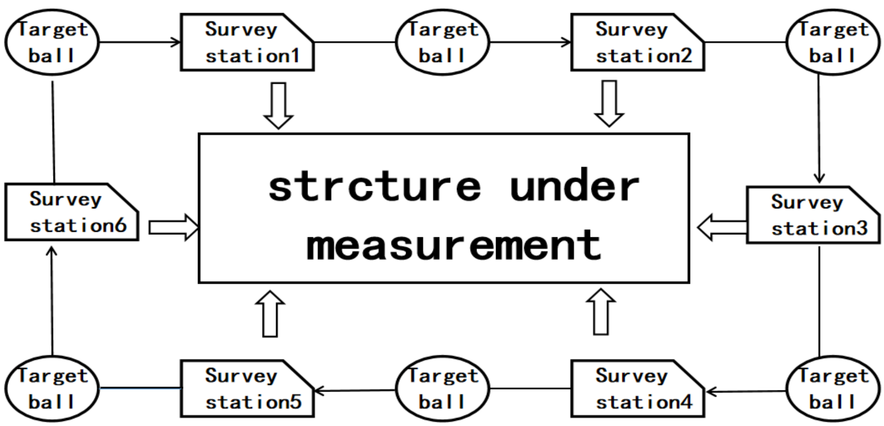


Fig. 3. Schematic diagram of scanning route

(3) Setting up target spheres: Between every two adjacent measurement stations, 2-4 fixed-position and fixed-diameter target spheres should be placed to facilitate the alignment of data collected from the two stations.

(4) Parameter setting: Determine the density of the three-dimensional laser scanning points, the maximum scanning distance, color, etc., based on environ-mental conditions, data accuracy requirements, and data processing speed requirements.

(5) Laser scanning: Following the predetermined scanning route and ensuring a static surrounding environment, fixed target sphere positions, and reasonable parameter settings, sequentially conduct three-dimensional laser scanning at each station to acquire point cloud data of the structure's geometry.

4.2 Advanced Point Cloud Data Processing Techniques for Complex Members

After scanning the truss members with a 3D laser scanner, the raw data obtained needs to undergo preprocessing, which involves further processing the raw data to eliminate outlier data, supplement missing data, smooth noisy data, etc. This process helps make the point cloud data more complete and accurate.

The quality of the raw scan data is determined by various factors such as the instrument properties of the scanner, scanning environment, scanning method, and many uncertainties. Errors are inevitable during the data collection process, which can reduce the quality of actual measurement data. The massive point cloud data often contain a significant amount of noise points and background object clutter, which can lead to missing or duplicated data in representing the 3D model.

Therefore, the raw data is not suitable for direct modeling. To maximize the authenticity of the target object and meet modeling requirements, preprocessing steps such as point cloud registration, data denoising, point cloud filtering, data meshing, simplification, etc., are necessary to obtain point cloud data that meets modeling requirements before proceeding with further modeling.

Using the Faro scanner point cloud processing software Scene for data pro-cessing, after importing the scanned raw data, create the scan point cloud, auto-matically perform denoising, and utilize photos captured synchronously with the scanner to transform the black-and-white point cloud into a colored point cloud based on image calculations.

Due to the limited area covered by each scanned site, it is necessary to merge data from multiple sites. The merging follows two principles: first, it must involve two sites with a common scanned area; second, it must use target spheres at the same position as common features for merging.

The target spheres must correspond one-to-one, and the higher the number and density of target spheres, the higher the accuracy of the merge. Specify control point coordinates in the model to place the model directly in the local coordinate system. Select parameters such as the structure range, point cloud accuracy, and format for export, then export processed point cloud data. This exported data can be used for subsequent virtual assembly and collision analysis. Scene supports exporting in common point cloud formats such as e57, xyz, las, pts, etc.

Based on the accurately measured and constructed model, input the current construction state model into the platform. Simultaneously, import the BIM mod-el and the oblique photography model into the platform. Disassemble the BIM model according to the construction lifting components into 630 main assembly modules, each module having at least 8 corner bolt hole 3D coordinates for systematic positioning. Use the coordinate data obtained from the scanned point cloud for calibration. The initially input model does not have coordinate positions. When the corresponding coordinate file is bound, it automatically jumps to display at that coordinate position, allowing for comparison with existing models as shown in Fig 4. Finally, export collision reports to provide feedback to construction personnel and manufacturers for further adjustment in design.

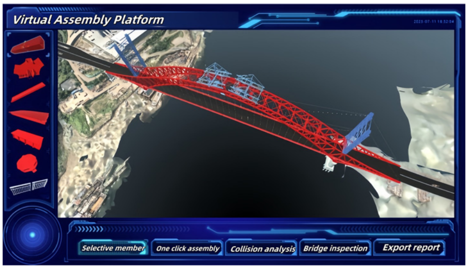


Fig. 4. Main interface and components of the virtual assembly platform

5 Digital Pre-Assembly Technology for Complex Members

Considering the actual progress of bridge site installation, there is a base model within the system that corresponds consistently to the on-site construction state coordinates and is updated in real-time[4]. Unassembled models are in a semi-transparent state for comparing and analyzing errors with the predicted BIM model. Each component in the BIM predicted model has a default set of feature point coordinates, numbering 8 or more. Imported components may use the system's provided coordinate values or the final machining coordinate values. Once models and coordinate values are bound upon import, the corresponding models can automatically jump to their installation positions. If there is an overlap with surrounding bolts or solid components exceeding a threshold, the color changes to blue, indicating a collision.

5.1 Importing Drawing Models or Pre-Fabricated as-built Models

The original model of the component before processing can be imported into the platform component library in ifc to gltf format for assembly, binding it with the corresponding component name. Additionally, the models that have already been processed can also be imported into the platform based on measured data after modeling as shown in Fig 5.

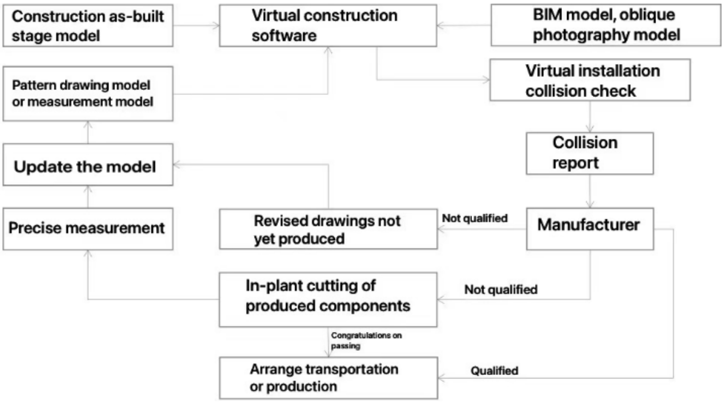
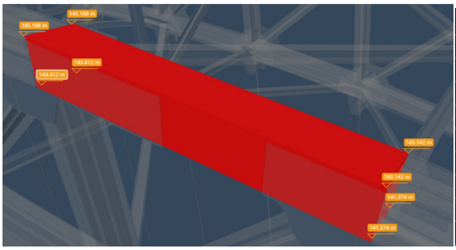


Fig. 5. Virtual assembly technology route

5.2 Importing Model Corner Point Bolt Hole XYZ Coordinate Data

The pre-processing data model's coordinates are default BIM coordinates, bindable directly for positioning. For processed models, based on the feature points of the component, point cloud scanning, and actual measurements, the relative coordinates of each feature point are combined to calculate and convert them into ab-solute coordinates in the virtual assembly BIM coordinate system as shown in Fig 6.



	A	B	C	D
1	Coordinate	x	y	z
2	1	100.065	1.368	134.253
3	2	100.065	3.068	134.253
4	3	99.565	1.368	132.539
5	4	99.565	3.068	132.539
6	5	87.431	1.368	130.441
7	6	87.431	3.068	130.441
8	7	87.931	1.368	128.727
9	8	87.931	3.068	128.727

Fig. 6. Assembly feature points of components and C4C5 coordinate values

5.3 Real-time Monitoring and Model Update

(1) Deformation monitoring technology

Various deformation monitoring technologies, such as total stations, levels, and strain gauges, are used on the construction site to obtain real-time deformation data of the structure. The total station can measure the three-dimensional coordinate changes of key points of the structure. The level is used to monitor the settlement of the structure. The strain gauge can reflect the stress and strain state inside the structure and indirectly infer the structural deformation. These monitoring data are transmitted to the virtual assembly system in real time.

(2) Dynamic model update

The virtual assembly system dynamically updates the virtual model of the structure according to the received deformation monitoring data. If a deviation is found between the actual structural deformation and the deformation predicted by the virtual model, the system will analyze the cause of the deviation. It may be due to inaccurate model parameters or unconsidered factors (such as unexpected external forces) that occur during the construction process. Then, adjust the model parameters according to the analysis results to keep the deformation state of the virtual model consistent with the actual structure, so as to provide accurate guidance for subsequent assembly construction.

5.4 Select Components in the Platform and Click "One-click Assembly Check Accuracy"

After importing models and coordinate values, you can select the current component to assemble, click on the one-click assembly button, and the component will appear in the assembly position. At the same time, the color will change to indicate collisions if any.

Fig. 7. Assembly correct and collision error

If there are no conflicts between the component installation and the installed structure or design information, the component will be displayed in a light red color. If there are conflicts between the component installation and the installed structure, or conflicts with the design information, the component will be dis-played in a light blue color as shown in Fig. 7

5.5 Collision Detection During the Lifting Process of the Members

The steel truss arch bridge's steel truss arch segments serve as support connections and feature I-shaped cross-sections. The upper and lower chords of the steel truss arch are connected in a diamond truss configuration, with a diagonal truss-style cross brace installed every two segments. Collision checks during the hoisting process are conducted using a coordinate path method that sets the starting and ending coordinates of the components. The component will ascend uniformly along the path, and during the ascent, it will assess whether it maintains a safe distance from surrounding installed components, thereby optimizing the hoisting plan as shown in Fig. 8

Fig. 8. Lifting simulation and collision visualization

5.6 Simulation of Standard Segment Assembly Process

The standard segments are installed symmetrically from the edge towards the mid-span and the actual bar coordinates are recorded to assess the virtual assembly error compared to the design values. If the error exceeds a threshold, it is evaluated, and a corresponding error value is generated for each assembled section. Linear values are measured and synchronized after the segment assembly is completed. After installation, the system analyzes the segment and calculates its cumulative deviation. Based on this deviation and the actual measurements taken on-site, the adjustment value for the assembly of the next segment is determined[5]. The virtual assembly process for segments 21-22 is as shown in Fig. 9 and Fig. 10:

Fig. 9. Installation of the lower chord member for B21B22 segment and installation of the diagonal member for A21C22 segment

Fig. 10. Installation of segments H21a and X9a and segment analysis prediction

5.7 Export Report

When collisions occur, collision reports can be exported. These reports automatically capture the current collision interface, describe the collision issues, and provide feasibility suggestions. After exporting the report, further optimizations can be continued, sent to the manufacturer for evaluation and adjustments, or used to develop necessary construction optimization plans and hoisting schemes for components already on-site as shown in the Table.1, Table. 2 and Fig 11.

Table 1. Collision detection report

Assembly components	Accuracy of feature point positioning	Presence of physical collisions	Feasibility of processing and cutting
C4C5	100%	None	Yes

Table 2. Coordinate points

Coordinate	x	y	z
1	100.065	1.368	134.253
2	100.065	3.068	134.253
3	99.565	1.368	132.539
4	99.565	3.068	132.539
5	87.431	1.368	130.441
6	87.431	3.068	130.441
7	87.931	1.368	128.727
8	87.931	3.068	128.727

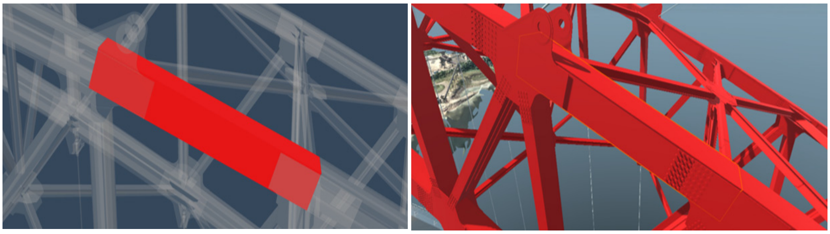


Fig. 11. Pre-assembly collision report

6 Conclusion

This paper studies virtual assembly using BIM+3D scanning on the Qingshuitang Bridge, arranging scanner points, processing data, and comparing with total station data. The results show that:

(1) Reverse modeling research using BIM and 3D laser scanning involves obtaining "point cloud" data, creating digital components reflecting errors, and integrating them into the BIM model for virtual assembly. The assembly results show that the component

accuracy meets installation requirements and does not affect the installation of the main arch segments. Combining virtual of actual steel components provides technical support for the precise installation of complex truss structures in bridge construction.

(2) This refined installation management method enables the rapid generation of a digital twin model for steel truss bridges. Analysis of its production accuracy reveals a maximum relative error of 5%, meeting precision requirements. Through virtual assembly, potential assembly issues that may arise on-site due to cumulative errors can be predicted, enhancing the efficiency of on-site assembly for steel truss bridges. This approach effectively prevents cost wastage resulting from insufficient precision.

(3) Virtual assembly allows for limited avoidance of rework and improved collaboration and operational efficiency. Labor and material costs are reduced to a significant degree compared to traditional pre-assembly.

The project has carried out applied research on virtual assembly using BIM + three-dimensional laser scanning technology, which has improved the refined management technology of assembly construction in complex steel truss arch spaces. Although building information technology has moved from automation, digitization, and networking to intelligence, from the perspective of practical application, building intelligence still remains in the initial stage. The integration of BIM and 3D laser scanning in virtual assembly has limitations in aspects such as data accuracy and compatibility, model processing and computing, personnel and technology, application scope and cost-effectiveness. Future research can address challenges from aspects such as improving data accuracy and compatibility, optimizing model processing and computing, strengthening personnel training and technological innovation, expanding applications and evaluating cost-effectiveness.

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