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Research on Detection Technology for Connection Joints of Prefabricated Concrete Bridges

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Abstract: Rational inspection is crucial for ensuring the quality of connection joints in prefabricated concrete bridges. Based on a specific prefabricated concrete bridge project, this study established a detection framework according to the inspection requirements for its connection joints and developed a combined application scheme for multiple detection techniques. Practical application demonstrates that the proposed detection scheme yields significant results and is expected to serve as a reference for subsequent research and practice on quality inspection technologies for connection joints of prefabricated concrete bridges.

Keywords: Prefabricated concrete bridge; Infrared thermography; Ultrasonic nondestructive testing; Electromagnetic induction testing; Rebound hammer testing

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1. Introduction

Prefabricated concrete bridges offer higher construction efficiency and environmental benefits compared with traditional castinplace concrete bridges, and have thus become a mainstream technical direction in bridge engineering. The most critical loadbearing points of such bridges are the connection joints, which play a decisive role in the overall bearing capacity, stability, safety, and durability of the bridge. However, existing inspection techniques suffer from shortcomings such as insufficient refinement, weak specificity, and poor adaptability, making it difficult to accurately detect hidden defects in connection joints [1]. To address these issues, this study draws upon an actual engineering case and adopts a combination of multiple advanced detection techniques for joint inspection, with the aim of providing a reference for similar projects in the future.

2. Project overview

The main superstructure of a certain prefabricated bridge project consists of prefabricated prestressed concrete box girders. The bearing pads, bent caps, and pier columns are all factoryprefabricated components and transported to the site for assembly after passing inspection. The connection joints include various types, such as bearing connection nodes, bent cap splicing seams, pier column grout sleeve connections, and box girder wet joints. The total bridge length is 186 m, the deck width is 24 m, and the design speed is 50 km/h. The bridge primarily serves urban road traffic while also fulfilling urban landscape functions. Given that the entire bridge is constructed using prefabricated concrete techniques, the connection structures are fairly representative, and the number of joint nodes is considerable. To prevent connection misalignment during construction or operation, the project owner imposed stringent requirements on the inspection techniques for connection joints. This paper focuses on the practical application of these inspection technologies.

3. Inspection requirements and framework for connection joints

3.1. Inspection requirements

Based on the fundamental structure and operating conditions of the prefabricated concrete bridge in this project, the connection joints are subject to prolonged influences from thermal stress, vehicle loads, and environmental erosion, making them susceptible to hidden defects. Accordingly, the following main inspection requirements are established for the connection joints (**Table 1**).

Table 1. Main inspection requirements for connection components

No.	Connection Location	Inspection Requirement	Inspection Purpose
1	Pier column sleeve	Detect whether grouting is compact, whether there are voids, and whether rebar anchorage is insufficient, etc.	Ensure vertical loadbearing connection performance
2	Wet joint of precast components	Detect whether concrete has hollowing, cracking, water leakage, or poor bonding, etc.	Ensure transverse connection performance
3	Bearing connection joint	Detect whether there is void, displacement, bolt loosening, or aging deformation, etc.	Keep the force transmission of the bridge uniform
4	Splice joint	Strengthen detection of joint carbonization, crack expansion, and steel reinforcement corrosion, etc.	Achieve reasonable evaluation of structural durability

3.2. Testing approach

Based on the general overview of the project and the primary testing requirements for the connection joints of prefabricated concrete bridges, the testing organization has designed an overall technical strategy that follows the principles of comprehensive nondestructive testing, localized verification, and fullprocess refinement. First, visual inspection and infrared scanning are used for a general survey of the connection joints to achieve preliminary identification of suspected defect areas. Subsequently, nondestructive testing techniques such as ultrasonic testing, electromagnetic induction, and rebound hammer testing are applied to conduct specialized inspections on suspected defective locations, so as to accurately determine the defect location, size, and severity [2]. Finally, a small number of borehole verification tests are carried out on difficult and critical points to ensure the accuracy and reliability of the test data. This entire set of technical procedures effectively balances testing precision and efficiency, adapts well to the actual conditions of the project, and thus enables comprehensive testing of all connection nodes.

4. Application practice of connection joint testing techniques

4.1. Visual inspection and infrared thermography survey

To enable rapid identification of both apparent and hidden defects in the connection joints of prefabricated concrete bridges, the testing organization adopted visual inspection and infrared thermography as the fundamental survey techniques. The selected equipment included a portable infrared thermal imager and a highdefinition industrial camera, with a temperature measurement range of –20 °C to 150 °C and an accuracy within ±0.05 °C. Prior to testing, dust, debris, and standing water on the surface of the test areas were thoroughly cleaned to keep the testing surface flat and clean, thereby preventing environmental interference with the test results. The connection nodes of the entire bridge were then divided into several test units according to different zones, and each unit was numbered to avoid omissions or duplicate testing [3]. Following that, the formal testing process commenced. In this step, visual inspection was first performed to examine each connection joint for apparent defects, including component misalignment, bolt loosening, water seepage, and joint cracking, with precise recording of defect locations and sizes, and retention of photographic documentation. Next, infrared thermal imaging equipment was used for scanning inspection, with the vertical distance between the device and the test surface controlled at 0.8–1.2 m and the scanning speed kept at ≤0.2 m/s, so as to comprehensively collect temperature field data for each area. By comparing the temperature difference characteristics between normal areas and defective areas, hidden defects such as joint hollowing and grouting voids could be accurately identified, thereby completing the preliminary screening of defects and suspected locations.

4.2. Ultrasonic nondestructive testing for density

For the sleeve connections and wet joints of the prefabricated concrete bridge in this project, the testing organization primarily employed ultrasonic nondestructive testing to examine their density, enabling accurate identification of internal defects such as concrete loosening, hollowing, and bond failure [4]. The testing equipment used was an ultrasonic tester, with a measurement range of 0.5–5 m and a timeofflight accuracy of 0.1 μs. The first step in testing was to rationally arrange test points according to the inspection areas. For the sleeve areas, test points were arranged in four columns along the perimeter of the pier columns, with spacing controlled at 20 cm; for the wet joints, test points were arranged in a staggered doublerow pattern with spacing at 15 cm to ensure full coverage of the inspection. The second step was to uniformly apply a couplant on the test probes to eliminate air gaps and ensure stable ultrasonic wave transmission, with the couplant thickness controlled at 1–2 mm. The third step was to calibrate the equipment parameters on intact concrete areas, so as to determine the reference wave velocity, frequency, and amplitude. The fourth step involved using dual probes placed stably and closely against the test points to transmit ultrasonic waves and receive echoes; each test point was measured three consecutive times, and the average value was recorded as the final test value. Defect determination was made by comparing the measured data with the reference parameters. If the ultrasonic amplitude attenuation at a test point reached 20% or more, or if abnormal prolongation of the travel time occurred, the corresponding location was determined to be defective. Further crosscomparison of multipoint data was then performed to accurately pinpoint the specific location, defect burial depth, and size.

4.3. Electromagnetic induction testing for reinforcement connections

In this project, the testing organization mainly utilized electromagnetic induction testing to conduct a specialized inspection of the reinforcement connection effectiveness inside grouted sleeves, so as to accurately determine defects such as insufficient anchorage length, misalignment, and displacement of rebars, thereby preventing compromised joint stiffness and bearing capacity due to poor internal reinforcement connections [5]. A portable rebar scanner was selected as the testing device, with a detection depth range of 0–120 mm and an accuracy of ±0.5 mm, which matched the actual testing requirements for the φ25 and φ28 connecting rebars used in the connection joints of this prefabricated concrete bridge. Onsite testing commenced with precise marking of the specific test areas for the sleeves, while avoiding embedded pipes or metal components that could interfere with the testing signals. The equipment was then turned on, preheated for 5 minutes, and zerocalibrated; key parameters such as the reinforcement specifications and cover thickness at the connection joints were entered into the device as reference values. Subsequently, the probe was placed parallel and flush against the concrete surface, and scanning was performed both horizontally and vertically at a speed of 0.15 m/s, enabling continuous acquisition of reinforcement distribution data inside the connection joints. The equipment automatically generated core parameters such as anchorage length and spacing of the rebars; by comparing these with the preentered standard values, defects such as rebar misalignment or insufficient anchorage could be promptly detected. Finally, for any abnormal data points identified, two additional scans were performed with the electromagnetic induction device to verify the defects, thus effectively eliminating environmental and equipment interference and ensuring true and accurate determination of reinforcement connection defects [6].

4.4. Rebound hammer testing for joint compressive strength

For the compressive strength of concrete at the wet joints and splicing joints of the prefabricated concrete bridge, the testing organization selected rebound hammer testing as the preferred method in this project, using this technique to assist in evaluating the concrete pouring and curing quality at the joints, thereby achieving precise identification of hidden weak connections. A concrete rebound hammer with standardized impact energy was used as the basic testing device, and the standardized operating procedures were strictly followed according to the equipment instruction manual. In each wet joint area, 16 rebound test points were uniformly arranged, with spacing controlled at 30 mm or more, and care was taken to avoid areas with damage, honeycombing, or surface roughness that could interfere with the test results. Before testing, the test point surfaces were ground smooth using a grinding wheel; after treatment, loose aggregates, oil stains, and laitance were thoroughly removed to ensure a solid and flat testing surface [7]. The tester then held the rebound hammer perpendicular to the testing surface and applied pressure slowly, uniformly, and vertically; after the pointer locked, the reading was recorded. Each test point was subjected to a single rebound test only, to avoid repeated operations that could reduce testing accuracy. At the same time, the measured data were reasonably corrected using parameters such as carbonation depth and testing angle. Finally, the conformity of the joint quality was determined by comparing the measured data with the designed concrete strength parameters.

4.5. Local borehole verification testing

For the connection joints of the prefabricated concrete bridge in this project, in order to compensate for the limitations of the above nondestructive testing techniques and to address highrisk points that could not be precisely determined by NDT methods, the testing organization adopted local borehole testing as a minimally invasive auxiliary verification measure, thereby further improving the accuracy of joint defect detection. During the actual testing, small drilling machines, highdefinition endoscopes, and precision depth gauges were used as basic auxiliary equipment, and the auxiliary retesting was carried out strictly in accordance with the following operational procedures and technical measures [8]. First, the internal voids and density anomaly points identified during infrared and ultrasonic testing were screened out. Second, 1–2 borehole test points were set at each selected location according to the actual conditions; lowspeed drilling was performed using a φ10 mm drill bit, with the drill bit kept perpendicular to the component surface throughout, and the drilling depth extended approximately 5 cm beyond the suspected defect depth. Drilling force was carefully controlled to prevent violent drilling from enlarging the damage at the connection joints. Third, after drilling was completed, the testing personnel promptly cleaned the dust from inside the boreholes. Fourth, the endoscope was inserted into the borehole to directly visualize the actual condition of defects such as grouting compactness, looseness, voids, and rebar corrosion. Fifth, the defect burial depth and size were accurately measured using the depth gauge, and the specific measurement data were completely recorded simultaneously. After the verification testing was completed, the testing organization used fixed repair mortar to patch the boreholes and strengthened the curing of the repaired areas, thereby maintaining the structural integrity of the components and reasonably restoring their structural performance [9]. In this way, both the testing accuracy of the connection joints could be ensured, and the overall integrity of the prefabricated concrete bridge structure could be maximally preserved.

5. Application effectiveness of connection joint testing techniques

For the prefabricated concrete bridge selected in this study, after the fulldimensional quality testing of its connection joints using the above technical scheme, the problems of traditional manual testing—such as numerous loopholes, poor accuracy, and lack of specificity—were comprehensively addressed. As a result, full coverage and refined defect detection of all connection joints across the entire bridge were achieved. Moreover, both testing accuracy and efficiency were significantly improved compared with traditional manual testing methods, thus providing more accurate testing data support for subsequent quality acceptance, bridge operation and maintenance, and defect treatment. Practical application revealed that, compared with traditional manual testing techniques, the testing scheme applied in this project did not cause extensive structural damage, thereby achieving a balance between testing quality and costeffectiveness. Through a comparison of key core indicators (including detection rate of hidden defects, accuracy of test data, defect localization error, total bridge inspection time, and component damage degree), it can be seen that the testing effectiveness of this scheme was significantly superior to that of traditional testing techniques. The comparison of basic data is shown in **Table 2**.

Table 2. Comparison of core indicator parameters between the testing technical scheme used in this project and the traditional testing scheme

No.	Indicator	Proposed technology	Conventional technology	Improvement
1	Detection rate of hidden defects (%)	97.5	68.2	42.96%
2	Data accuracy rate (%)	98.1	82.5	18.91%
3	Defect localization error (mm)	±3	±15	80.00%
4	Full-bridge inspection time (d)	4	7	42.90%
5	Component damage degree (%)	0.1	3.2	96.88%

The comparison of the above testing data demonstrates that the technical testing scheme applied in this project outperforms traditional manual testing methods across all indicators, achieving a significant improvement in detection accuracy, further reducing testing time, and minimizing component damage. This confirms that the integrated technical scheme delivers notable practical results and exhibits excellent adaptability and feasibility. If this scheme is reasonably applied to subsequent similar projects, with appropriate detailed adjustments made according to actual conditions, it can also achieve favorable outcomes and provide transferable experience for future projects [10].

6. Conclusion

In summary, this paper, grounded in the practical project of testing connection joints in prefabricated bridge engineering, has established a comprehensive testing technology system through the integration of survey screening, precision testing, and minimally invasive verification, while rationally detailing the operational procedures of the overall testing process. Practice has confirmed that the combined application of nondestructive testing techniques can substantially enhance both the accuracy and efficiency of quality inspection for connection joints, and the final minimally invasive verification further ensures testing precision, thereby creating favorable conditions for quality control, safe operation, and maintenance of the overall prefabricated concrete bridge project. In the future, testing organizations may also consider introducing artificial intelligence technologies and corresponding equipment based on actual needs, or integrating advanced technologies such as digital twins and big data, to enable intelligent identification, rating, and early warning of various defects at connection joints, thereby achieving further optimization of the entire testing workflow.

Disclosure statement

The authors declare no conflict of interest.

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