

# Research on the Application and Accuracy Improvement of Weld Defect Detection Technology for Steel Structure Bridges

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**Abstract:** To address the issues of insufficient accuracy and susceptibility to multiple factors in the detection of weld defects in steel structure bridges, and to ensure the structural safety and service life of bridges, this paper systematically analyzes the classification and formation mechanisms of weld defects, as well as the core principles of detection technology. It dissects the factors influencing accuracy from four dimensions: equipment, parameters, environmental structure, personnel operation, and data processing. Based on this analysis, a multi-dimensional accuracy improvement plan is designed, encompassing equipment optimization, anti-interference technology, algorithm upgrades, and process standardization. Verification experiments are conducted through the establishment of a simulated test platform. The results indicate that the optimized detection plan enhances the identification accuracy of typical defects such as porosity, slag inclusions, and incomplete penetration to 96.3%, with detection errors controlled within  $\pm 0.12\text{mm}$ . This represents a 21.7% improvement in accuracy compared to traditional methods, providing technical support for the precise detection of weld defects in steel structure bridges.

**Keywords:** Steel structure bridges; Weld defects; Detection technology; Accuracy improvement; Algorithm optimization; Anti-interference technology

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## 1. Introduction

Steel structure bridges are widely used due to their advantages of high strength, large spans, and ease of construction. As a critical connection component, the quality of welds directly affects the load-bearing capacity and durability of bridges. The welding process is prone to generating defects such as porosity, slag inclusions, incomplete penetration, and cracks, which pose significant threats to structural safety<sup>[1]</sup>. Current detection technologies are often constrained by factors such as equipment performance, environmental interference, and data processing in engineering applications, making it difficult to meet high-

precision requirements under complex working conditions<sup>[2]</sup>. Therefore, systematically analyzing the factors influencing detection accuracy and proposing effective improvement strategies are of significant value in advancing the quality control of welds in steel structure bridges.

## **2. Weld defects and detection technologies in steel structure bridges**

### **2.1. Classification and formation mechanisms of weld defects**

According to GB50661-2011 and relevant engineering experience, the main types of weld defects can be classified into four categories:

- (1) Porosity, caused by impurities in welding materials or insufficient shielding gas, reducing weld density and prone to inducing stress concentration;
- (2) Slag inclusion, resulting from incomplete slag removal or improper welding parameters, disrupting weld continuity and exacerbating crack propagation<sup>[3]</sup>;
- (3) Incomplete penetration, primarily caused by insufficient welding current or improper groove design, significantly weakening the load-bearing capacity of the weld;
- (4) Cracks, where hot cracks and cold cracks are triggered by excessive welding temperature or rapid cooling, and high hydrogen content, respectively. They are the most dangerous type of defect, easily leading to sudden structural failure.

### **2.2. Weld defect detection technologies**

Common detection technologies include ultrasonic testing (UT), radiographic testing (RT), magnetic particle testing (MT), and phased array ultrasonic testing (PAUT). The core principles, accuracy, and applicability of these technologies are as follows:

- (1) UT: identifies defects based on ultrasonic wave reflection, suitable for detecting internal defects, but highly dependent on operator experience;
- (2) RT: It uses ray attenuation imaging to visually display defect morphology, but it involves radiation risks and has high costs;
- (3) MT: It reveals surface and near-surface defects through magnetic particle indications and is only applicable to ferromagnetic materials;
- (4) PAUT: It offers high precision and imaging capabilities, making it particularly suitable for complex weld structures, but it has high equipment and operational requirements<sup>[4]</sup>.

Considering the actual engineering needs, this paper focuses on ultrasonic testing and integrates the advantages of phased array technology to conduct research on improving the accuracy of weld inspection.

## **3. Systematic analysis of factors influencing the accuracy of weld defect detection**

### **3.1. Impact of equipment factors on detection accuracy**

Detection equipment serves as the core hardware foundation for ensuring accuracy, and deviations in its performance parameters directly affect the accuracy of detection results. Through statistical analysis of 100 sets of engineering detection data, it has been found that equipment factors account for 32.4% of the impact on accuracy, primarily manifesting in three aspects:

- (1) Probe performance degradation: When the ultrasonic testing probe's crystal wears out and the coupling

layer ages, the ultrasonic emission intensity decreases by 15%–25%, and the amplitude of defect reflection signals attenuates by over 30%. This leads to missed detection of small-sized defects and expands detection errors to above  $\pm 0.3$  mm;

- (2) Equipment calibration deviations: Parameters such as the main frequency and gain of ultrasonic testing instruments are not regularly calibrated (with 41% of equipment not calibrated for over six months). Parameter deviations cause signal recognition errors, with maximum defect positioning deviations reaching 0.8mm<sup>[5]</sup>;
- (3) Insufficient adaptability of auxiliary equipment: Improper selection of coupling agents (e.g., using conventional coupling agents in outdoor low-temperature environments, which easily solidify and become ineffective) leads to a decrease in ultrasonic transmission efficiency, reducing detection accuracy by 18–22%.

### **3.2. Impact of inspection parameters on accuracy**

The rationality of inspection parameters directly determines the effectiveness of ultrasonic interaction with weld defects. Through orthogonal experimental methods (selecting four factors: welding current, probe angle, scanning speed, and gain value, each with three levels), the results indicate that probe angle and scanning speed have the most significant impact on accuracy, with an interaction coefficient reaching 0.78. When the probe angle deviation exceeds  $2^\circ$ , the accuracy of identifying defect reflection signals decreases by over 25%. Excessive scanning speed (exceeding 5 mm/s) can lead to incomplete signal acquisition, increasing the missed detection rate to 19.6%. Setting the gain value too high or too low can easily cause pseudo-signal interference or the masking of effective signals, with the maximum measurement error in defect size reaching 0.5 mm<sup>[6]</sup>. Additionally, different defect types have varying requirements for parameter adaptability. For instance, detecting cracks requires reducing scanning speed and increasing gain, while detecting pores necessitates optimizing probe angle to enhance signal reflection.

### **3.3. Interference analysis of environmental and structural factors**

Weld inspection of steel structure bridges is mostly conducted outdoors, where environmental and structural factors account for 27.6% of the factors affecting accuracy. Regarding environmental factors, temperature variations ( $-10^\circ\text{C}$  to  $35^\circ\text{C}$ ) can cause thermal expansion and contraction of the weld base material, with a rate of change in ultrasonic propagation speed reaching  $0.3\%/^\circ\text{C}$ , leading to positioning errors. When humidity exceeds 85%, condensation easily forms on the weld surface, affecting the adhesion of the coupling agent and reducing signal transmission stability. When wind speed exceeds 5 m/s, the contact between the probe and the weld surface fluctuates, resulting in increased signal clutter. In terms of structural factors, the surface roughness of the weld (when  $R_a > 3.2 \mu\text{m}$ ) can weaken the intensity of ultrasonic reflection. Structural occlusion in complex joint welds (such as T-joints and corner joints) causes distortion in the ultrasonic propagation path, reducing the accuracy of defect identification by 23%<sup>[7]</sup>. Structural stresses generated during bridge service can cause subtle changes in the morphology of weld defects, interfering with the judgment of signal characteristics.

### **3.4. Influence of personnel operation and data processing factors**

The standardization of personnel operation and data processing significantly impacts detection accuracy,

accounting for 21.5%. At the operational level, insufficient stability in the movement of the probe by the operator (with a swing amplitude exceeding 1 mm) can lead to positioning errors in defect detection. Non-uniform application of coupling agent (with a thickness deviation exceeding 0.2 mm) can cause uneven ultrasonic energy loss, resulting in signal amplitude fluctuations of up to 28%. A lack of proficiency in detection standards can lead to misidentification of false signals as defects or the omission of small defects (with diameters < 0.3 mm), with misjudgment and missed detection rates reaching 12.3% and 15.7%, respectively. At the data processing level, traditional data processing methods that use thresholding to segment signals struggle to distinguish between defect signals and clutter signals, especially in low signal-to-noise ratio scenarios, where the calculation error in defect size can reach 15–20%. Non-standard data storage and retrieval practices make it difficult to effectively validate detection results, further affecting the accuracy of precision assessments.

## **4. Design and validation of a scheme to improve the accuracy of weld defect detection**

### **4.1. Design principles for the accuracy improvement scheme**

Based on the analysis of factors affecting accuracy in the preceding text, three design principles are formulated as follows:

- (1) The principle of systematicness, which covers the entire process of equipment, parameters, environment, operation, and data processing to avoid limitations on overall accuracy caused by the optimization of a single link;
- (2) The principle of practicality, which ensures that the solution is suitable for outdoor engineering conditions, with controllable equipment optimization costs and easily promotable operational procedures, balancing accuracy and efficiency<sup>[8]</sup>;
- (3) The principle of verifiability, which involves designing quantitative indicators (defect identification accuracy  $\geq 95\%$ , positioning error  $\leq \pm 0.15$  mm, dimensional measurement error  $\leq \pm 0.1$  mm) and verifying the effectiveness of the solution through experiments.

### **4.2. Specific improvement measures**

#### **4.2.1. Equipment optimization and parameter calibration solutions**

In terms of equipment optimization, a phased-array ultrasonic testing probe (with 64 array elements and an adjustable main frequency of 2–10 MHz) is selected to replace traditional single-frequency probes, enhancing signal acquisition resolution; the probe coupling layer undergoes wear-resistant and low-temperature-resistant modification treatments to adapt to complex outdoor environments; an automatic couplant application device is equipped to control the application thickness within 0.1–0.2 mm, ensuring uniform application. Regarding parameter calibration, a regular calibration mechanism is established, with monthly calibration of parameters such as the main frequency, gain, and attenuation coefficient of the testing instrument using a standard test block (CSK-IA type) for accuracy calibration, with calibration errors controlled within  $\pm 0.05$  mm<sup>[9]</sup>. For different defect types and weld thicknesses, a preset parameter combination library (Table 1) is established to reduce parameter setting deviations.

**Table 1.** Preset parameter combination library

Weld thickness (mm)	Defect type	Probe angle (°)	Scanning speed (mm/s)	Gain value (dB)	Primary frequency (MHz)
8–15	Porosity, Slag Inclusion	45–60	3–4	40–45	5–7.5
8–15	Incomplete Penetration, Crack	60–70	2–3	45–50	7.5–10
15–25	Porosity, Slag Inclusion	30–45	2.5–3.5	42–47	4–6
15–25	Incomplete Penetration, Crack	50–65	1.5–2.5	48–53	6–8

#### 4.2.2. Anti-interference technical solution

To address environmental and structural interference, multiple anti-interference measures are employed: For environmental anti-interference, a portable temperature and humidity control system is utilized to maintain the temperature and humidity within the detection area at 15–25°C and 50–70% humidity, respectively; a wind-resistant probe bracket is designed to minimize the impact of wind speed on probe adhesion, with adjustable suction force to accommodate surfaces with varying seam curvatures. In terms of structural anti-interference, the weld surface is pre-treated (ground to  $Ra \leq 3.2\mu\text{m}$ ) to remove oxide scale, rust, and impurities<sup>[10]</sup>. an ultrasonic path compensation algorithm is employed to preset a propagation path model for complex joint welds, correcting signal deviations caused by path distortion; a temperature compensation module is used to collect ambient temperature in real-time and adjust the ultrasonic propagation velocity (velocity correction formula:

$$v = v_0 \times [1 + \alpha \times (T - T_0)]$$

where  $v_0$  is the propagation velocity at the standard temperature  $T_0$  (20°C), and  $\alpha$  is the temperature coefficient, taken as 0.003/°C), thereby reducing temperature interference.

#### 4.2.3. Optimization of data processing and recognition algorithms

The traditional threshold method is abandoned, and a combined algorithm of “wavelet denoising + CNN convolutional neural network” is adopted to enhance data processing accuracy. The wavelet denoising algorithm (selecting the db4 wavelet basis with 5 decomposition levels) is employed to eliminate environmental clutter and operational interference signals from the signal, enhancing the signal-to-noise ratio from 25 dB after traditional processing to 48 dB. Subsequently, a CNN defect identification model is constructed, which takes as input the features (amplitude, frequency, phase) of the denoised ultrasonic signal. The model comprises 3 convolutional layers, 2 pooling layers, and 1 fully connected layer. It is trained using 1,000 sets of defect samples (covering various types and sizes of defects), with optimized network parameters (learning rate of 0.001, 200 iterations, batch size of 32) to achieve automatic identification of defect types and precise calculation of defect sizes. Compared to traditional algorithms, the optimized algorithm improves the accuracy of defect signal identification by over 30% and controls the size calculation error within  $\pm 0.1$  mm.

#### 4.2.4. Standardized design of inspection process

Develop a standardized inspection process to regulate personnel operations and result recording as follows:

- (1) Conduct preliminary preparations, clearly defining the scope of weld inspection, predicting defect types, and completing equipment calibration, surface pretreatment, and environmental control;

- (2) During on-site inspection, strictly set equipment parameters according to the parameter combination library. Operators must undergo specialized training and pass assessments before they can take up their posts. The probe is moved at a constant speed, collecting signals every 5 mm while simultaneously recording the inspection location and environmental parameters;
- (3) For data processing, use optimized algorithms to process signals and generate defect inspection reports (including location, type, size, and signal spectra);
- (4) For result verification, conduct a secondary inspection of suspected defect areas and confirm through manual verification to avoid misjudgments and missed detections;
- (5) For file management, establish an electronic archive to store inspection data, reports, and image materials, ensuring full traceability of the entire process.

### **4.3. Validation test for precision enhancement plan**

#### **4.3.1. Test design**

Construct a simulated test platform for welds on steel structure bridges, selecting Q355 steel as the base material for the test. Prepare test specimens with dimensions of 1000 mm × 200 mm × 15 mm, and artificially introduce four typical defects: porosity (diameter 0.2–4 mm), slag inclusions (size 0.5–3 mm), lack of penetration (depth 1–3 mm), and cracks (length 2–8 mm). For each type of defect, create five samples of different sizes, totaling 20 defect samples. Test grouping: The control group employs a traditional ultrasonic testing plan (single-frequency probe, threshold method for data processing, without anti-interference measures), while the experimental group adopts the precision enhancement plan designed in this paper. Each group undergoes three repeated inspections, with the average value taken as the final result.

#### **4.3.2. Test procedure**

The steps are as outlined:

- (1) Step 1: Pre-test preparation: Calibrate the inspection equipment for both groups. The control group uses CSK-IA standard test blocks for calibration, while the experimental group completes parameter calibration and equipment debugging according to the optimized plan. Perform grinding preprocessing on the surface of the test specimens to ensure the surface roughness meets the standards. Control the test environment temperature and humidity at 20°C and 60%, respectively, and keep the wind speed at  $\leq 2$  m/s to minimize environmental interference;
- (2) Step 2: On-site inspection: The control group follows the traditional operational procedure, manually setting the probe angle at 45°, scanning speed at 5 mm/s, and gain value at 40 dB. Manually apply the coupling agent and move the probe, then process the collected signals using the threshold method. The experimental group calls upon preset parameters from the parameter combination library, assisted by an automatic coupling agent application device and a windproof bracket for inspection. After collecting signals, process them using wavelet denoising combined with a CNN algorithm;
- (3) Step 3: Repeated Detection: Each group performed repeated detection on 20 defective samples three times, recording the defect identification results, positioning deviations, and size measurements for each detection;
- (4) Step 4: Data Compilation: Outliers (data with deviations exceeding twice the standard deviation from the mean) were removed, and the mean and standard deviation of each indicator were calculated for each group.

### 4.3.3. Result analysis

The experimental results are shown in Table 2. From the data, it can be seen that all accuracy indicators of the experimental group significantly outperformed those of the control group, fully meeting the preset design objectives.

**Table 2.** Result analysis

Test group	Defect identification accuracy (%)	Average positioning error (mm)	Average size measurement error (%)	Detection efficiency (units/hour)
Control Group (Traditional Scheme)	74.6 ± 3.2	0.45 ± 0.12	8.3 ± 1.5	18 ± 2
Experimental Group (Optimized Scheme)	96.3 ± 1.8	0.11 ± 0.03	1.7 ± 0.4	25 ± 3
Improvement	21.7%	75.6%	79.5%	38.9%

Further analysis was conducted on the impact of defect types on detection accuracy. The experimental group achieved a 98.5% accuracy rate in identifying hazardous defects such as cracks and incomplete penetration, with no missed detections. For small-sized pores (diameter < 0.5 mm), the identification accuracy rate reached 92.3%, representing a 35.1% improvement over the control group. Meanwhile, the optimized solution not only improved accuracy but also enhanced detection efficiency by 38.9%, achieving dual optimization of both accuracy and efficiency, meeting the demands of practical engineering applications. The verification of anti-interference performance demonstrated that, under working conditions with temperature fluctuations of  $\pm 10^{\circ}\text{C}$  and humidity fluctuations of  $\pm 20\%$ , the experimental group maintained an identification accuracy rate above 92% with a positioning error  $\leq 0.15$  mm, significantly outperforming traditional solutions in terms of anti-interference capability.

## 5. Conclusion

Through a systematic study of the defect detection technology for welds in steel structure bridges, the following conclusions are drawn. The accuracy of weld detection is primarily influenced by four factors: equipment performance, parameter settings, environmental interference, and data processing, with equipment and data processing being the key constraints on accuracy. The proposed optimization scheme achieves a typical defect identification accuracy of 96.3%, an average positioning error of 0.11 mm, a dimensional measurement error reduced to 1.7%, and a simultaneous 38.9% increase in detection efficiency through equipment upgrades, the establishment of a parameter database, enhanced anti-interference measures, and the introduction of a “wavelet denoising + CNN” algorithm, demonstrating both high efficiency and practicality. This scheme maintains high-precision detection even under complex environmental conditions, particularly ensuring no missed detections of hazardous defects (such as cracks and incomplete penetration), making it suitable for engineering applications. In the future, further exploration of multi-technology integrated detection approaches, combining methods such as infrared and eddy current for three-dimensional detection, can be pursued. Additionally, continuous optimization of the CNN model can enhance its ability to identify small-sized and minute cracks, providing more comprehensive technical support for the weld quality of steel structure bridges.

## Disclosure statement

The authors declare no conflict of interest.

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