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Research on Inspection Technology and Application of Connection Joints in Steel Structure Bridges

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Abstract: To promptly identify and resolve quality issues in the connection joints of steel structure bridges and ensure the connection effectiveness of such bridges, this paper analyzes mainstream inspection technologies for welded joints, bolted joints, and riveted joints, based on the primary quality problems encountered in the connection joints of steel structure bridges. The aim is to provide references for the subsequent inspection of connection joints in steel structure bridge projects.

Keywords: Steel structure bridge; Welded connection joint; Bolted connection joint; Riveted connection joint; Inspection technology

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1. Introduction

Steel structure bridges, characterized by their high strength, large spans, and ease of construction, constitute a crucial component of modern transportation infrastructure. In steel structure bridges, connection joints serve as the core load-transmitting parts, and their quality directly impacts the overall quality, safety, and durability of the bridges. However, due to factors such as manufacturing quality, construction techniques, and prolonged continuous operation, connection joints may develop certain defects. If not promptly identified and addressed, the risk of structural failure will continuously increase [1]. Therefore, bridge engineering units should clarify the primary quality issues in their connection joints, employ targeted inspection technologies, ensure the maintenance effectiveness of connection joints, and provide technical support for the safe and long-term operation of steel structure bridges.

2. Main quality issues with connection joints of steel structure bridges

2.1. Quality issues with welded connection joints

Welding is currently the primary method for connecting steel structure bridges, utilizing techniques such as submerged arc welding and arc welding to join bridge steel materials, ensuring their strength and sealing properties. The main quality issues with such connection joints include surface and internal defects such as slag inclusions, porosity, crater cracks, undercutting, root shrinkage, and incomplete fusion. The primary causes of these quality issues typically include the following aspects:

(1) The welding materials and base materials are not sufficiently compatible, or impurities exist in the welding materials, adversely affecting the welding quality;

(2) The welding process parameters are not reasonably set, such as poor control of welding speed, voltage, and current, leading to excessive melting or insufficient penetration;

(3) The welding environment is not well controlled, with wind speed or humidity exceeding standards, reducing the stability of the molten pool;

(4) The surface is not thoroughly cleaned before welding, allowing impurities such as oxide layers and oil stains to enter the molten pool, causing slag inclusions;

(5) Rapid cooling after welding generates residual stresses, leading to cracks [2].

2.2. Quality issues with bolted connection joints

In the current connections of steel structure bridges, bolt connection is also a mainstream method. This method can be divided into two types: ordinary bolt connection and high-strength bolt connection. The basic technological principles of both methods rely on utilizing the tensile and shear forces of bolts or the frictional force at the contact surface to ensure effective force transmission. These methods feature easy installation and removal, making them suitable for on-site assembly connections in steel structure bridges. The main quality issues with such connection joints include thread damage, bolt loosening, corrosion and rusting, bolt bending, and insufficient pre-tensioning force, among others. The primary causes of these quality issues typically include the following aspects:

(1) Inadequate processing accuracy of bolt holes results in excessive diameter deviations, causing uneven stress distribution on the bolts;

(2) Poor alignment of hole positions during installation leads to forced insertion of bolts, resulting in bolt bending;

(3) Improper torque control or an excessively long interval between initial and final tightening causes the pre-tensioning force to fail to meet design requirements;

(4) Substandard bolt material quality leads to mechanical properties that do not match actual requirements, resulting in damage under tensile stress;

(5) The presence of corrosive media in the application environment causes bolt rusting, reducing cross-sectional strength;

(6) Prolonged exposure of connection joints to alternating loads leads to fatigue damage in the bolts [3].

2.3. Quality issues in riveting connection joints

Riveted connection was a common method used in early steel structure bridges. Although it has gradually been replaced by new connection methods such as welding and bolting, some existing old steel structure bridges still feature such connection joints. The basic principle of this connection method is to achieve a fixed connection between components and rivets through hot riveting, offering good toughness and plasticity. The main quality issues with such connection joints include rivet loosening, deformation, fracture, as well as cracks or fissures at the riveted positions. The primary causes of these quality problems typically include the following aspects:

(1) Insufficient heating temperature or uneven cooling of rivets during the riveting process adversely affects the tightness of the connection;

(2) Significant deviations in the dimensions of rivet holes adversely affect connection accuracy and load transfer effectiveness;

(3) Wear occurs between rivets and hole walls due to alternating loads during long-term service, leading to rivet loosening;

(4) Aging of rivet materials or the presence of corrosive media in the environment reduces rivet strength, resulting in cracks, fissures, or even fractures under prolonged high-intensity loads.

3. Key points in the application of main detection technologies for connection joints in steel structure bridges

3.1. Detection technology for welded connection joints

For welded connection joints in steel structure bridges, the current mainstream detection technologies include magnetic particle, ultrasonic, and radiographic methods. Given the two major categories of defects, surface and internal, in welded connection joints, inspectors should reasonably combine and utilize these three mainstream technologies based on actual conditions to conduct comprehensive inspections. This approach allows for the complementary advantages of each technology, thereby improving detection accuracy.

3.1.1. Magnetic particle testing technology

Among them, magnetic particle testing technology is applicable for detecting quality issues such as incomplete fusion and cracks on the surface and near-surface of welded joints. Its basic principle is based on the characteristic that a leakage magnetic field can attract magnetic particles and form magnetic traces. After magnetizing ferromagnetic materials, if there are defects at the inspection site, the magnetic flux at the defect location will be distorted, forming a leakage magnetic field. This field exerts a strong adsorption effect on dry magnetic particles or magnetic suspensions, thereby forming clearly visible magnetic traces at the defect location, revealing the specific position and shape of welding quality defects. During specific inspections, inspectors should follow these operational steps as follows:

(1) Remove impurities such as splatter, oxide scale, and oil from the surface of the area to be tested, and control the surface roughness of the area to be tested at Ra12.5μm or below to prevent magnetic particles from adhering to the surface of the area to be tested under non-adsorptive forces;

(2) Select the magnetization method reasonably according to the specific type of weld. If the weld is flat or curved, magnetization can be performed using the magnetic yoke method; if the weld is a corner joint or T-joint, magnetization can be performed using the cross magnetization method. When spraying magnetic suspensions using the wet method, strictly control the spraying pressure and flow rate according to the actual situation to prevent magnetic traces from being washed away.

At the same time, inspectors should also pay attention to the following two points during the inspection process:

(1) The magnetization intensity should be maintained adequately throughout the entire inspection process,

and the lifting power of the magnetic yoke should typically be controlled at 45N or above;

(2) The lighting conditions should meet actual requirements during the inspection; the brightness for white light inspection should not be lower than 500lx, and the ultraviolet wavelength for fluorescent inspection should be controlled at 365nm to ensure visual effects.

3.1.2. Ultrasonic testing technology

Ultrasonic testing technology is applicable for detecting quality defects such as slag inclusions, porosity, and lack of penetration within welded joints. Its fundamental principle relies on the differences in ultrasonic reflection and refraction at interfaces between different media. An ultrasonic emitter is used to transmit ultrasonic waves into the inspected area, while an ultrasonic receiver captures the reflected waves. By analyzing variations in the reflected wave signals, defects can be scientifically assessed [4]. During specific inspections, personnel can follow these steps and methods:

(1) Determine the frequency and angle of the ultrasonic probe based on the weld thickness. For thicker welds, a low-frequency probe should be preferred, and the angle between the probe and the inspection surface should be reduced. For thinner welds, a high-frequency probe is preferable, and the angle between the probe and the inspection surface can be appropriately increased;

(2) Fill a coupling agent between the probe and the inspection surface to ensure good contact and minimize ultrasonic energy loss;

(3) Conduct a uniform scan along the weld direction, typically at a speed below 150 mm/s, ensuring complete coverage of the entire weld area to avoid omissions.

Meanwhile, during ultrasonic testing, inspectors should also adhere to the following precautions:

(1) Calibrate the instrument and probe before testing to prevent equipment accuracy issues from affecting the inspection results;

(2) Grind the weld smooth in advance to ensure good contact between the probe and the inspection surface, thereby improving inspection accuracy;

(3) Accurately identify defect signals based on actual conditions to promptly and accurately detect weld quality defects [5].

3.1.3. Radiographic testing technology

Radiographic testing technology is applicable for detecting volumetric defects inside welded joints. Its fundamental principle is based on the penetrating characteristics of X-rays or gamma rays, utilizing digital imaging or film to record differences in ray attenuation. Since the density of defective areas is higher than that of the base metal, these areas absorb fewer rays, resulting in darker regions, or even black areas, on the images. During specific inspections, technicians should follow these steps and methods:

(1) Select the appropriate type of ray based on the thickness of the weld. For medium or thin welds, X-rays can be used for inspection; for thicker welds, gamma rays should be employed;

(2) Based on actual conditions and quality control requirements, use either the single-wall single-image radiography method or the double-wall double-image radiography method to ensure that the rays cover the entire inspection area and prevent any defects from being overlooked;

(3) Reasonably control the radiographic parameters according to the actual situation to ensure image clarity and contrast, enabling accurate assessment of quality defects.

During this process, inspectors should also pay attention to the following points:

(1) The operation of such inspection equipment is complex and costly, so specialized protective facilities should be provided during use to prevent equipment damage;

(2) This technology has relatively low sensitivity in detecting planar defects and needs to be used in conjunction with other techniques;

(3) During inspections, strict adherence to the safety specifications provided by the equipment manufacturer for radiation protection should be ensured to avoid radiation hazards [6].

3.2. Inspection technology for bolted connection joints

In the inspection of bolt connection joints in steel structure bridges, visual inspection, torque measurement, and ultrasonic testing techniques are the most commonly used. Through the effective combination of different inspection techniques, a complementary inspection technology system can be formed to accurately detect and identify various quality issues.

3.2.1. Visual inspection technology

Among them, visual inspection techniques are suitable for screening surface defects in bolt connection joints. The basic principle involves using direct observation methods such as the naked eye or a magnifying glass to inspect the appearance of bolts, nuts, washers, and other components at each connection joint, and to assess their quality defects based on their appearance. During specific inspections, inspectors should first choose a viewpoint that facilitates observation and examine the bolt heads, threads, nuts, and the connection areas between components. They can also use tools such as magnifying glasses and flashlights to enhance observation accuracy. When necessary, an endoscope can be used to inspect hidden areas. During this process, inspectors should ensure that any oil, dust, or other obstructions on the surface of the area to be inspected are cleared away in advance. They should also standardize the inspection process to minimize human influence. At the same time, visual inspection should be used in conjunction with other inspection techniques to improve the accuracy of detecting hidden defects and small cracks.

3.2.2. Torque measurement technology

Torque measurement is suitable for inspecting the pre-tension force in bolts. The basic principle involves using the relationship between torque and pre-tension force to measure the torque value during the tightening or loosening of bolts with a torque wrench, and to determine whether the bolt pre-tension force meets design requirements. During specific inspections, inspectors should follow the steps and methods outlined below:

(1) Prior to inspection, calibrate the torque wrench to ensure its measurement range covers 20–80% of the inspection torque;

(2) When conducting inspections using the reverse tightening method, gradually apply torque in the same direction as the nut tightening, observing whether the nut rotates when the inspection torque is reached;

(3) Determine the number of torque screenings reasonably based on the number of nodes, ensuring that the number of screened nodes is not less than 10% of the total number of nodes. For single steel structure bridges, the number of bolt connection nodes screened should be no less than 10, and the number of bolts screened at each node should be no less than 2.

During this process, inspectors should also pay attention to the following considerations:

(1) Conduct inspections in an order from the center outward to prevent bending deformation of components caused by adjustments to bolt tightening torque;
(2) Strictly determine the torque coefficient according to engineering design standards and accurately calculate torque to ensure inspection quality [7].

3.2.3. Ultrasonic testing for bolted joints

When conducting ultrasonic testing, inspectors should select appropriate inspection probes based on bolt sizes, control the inspection angle, and avoid interference areas to ensure the normal use of ultrasonic testing technology. After that, select exposed bolt ends on the inspection surface and move the probe along the diameter for inspection. After each movement, rotate the bolt by 5° or less to ensure 360° coverage of the inspected bolt, and control the inspection depth by reasonably adjusting the position and angle of the ultrasonic probe. During inspection, clean the probe and bolt cross-sections to ensure effective filling of the coupling agent. Meanwhile, analyze inspection results based on the specific structural characteristics of the bolts to prevent interference from false signals.

3.3. Inspection technology for riveted connection nodes

For riveted connection nodes in steel structure bridges, the most commonly used inspection techniques during specific inspections include tapping, infrared thermography, and ultrasonic technology.

3.3.1. Tapping inspection technology

Among them, the tapping inspection technique is suitable for quickly assessing the tightness of riveted connections. Its basic principle involves using a specialized hand hammer to tap rivets and analyzing the resulting vibrations or acoustic anomalies through sensors or auditory perception. Based on differences in signal amplitude and frequency, the technique determines the looseness of rivets and internal defects. During specific inspections, inspectors should first reasonably select an inspection hammer according to the rivet material and determine the impact force during tapping to match the actual condition of the rivets. Each rivet should be tapped individually, and the sound differences should be monitored. If the rivet connection is tight, the tapping sound will be very crisp; if there is looseness or defects, a dull sound will be emitted. Additionally, semi-quantitative analysis of vibrations can be conducted using an acceleration sensor to further improve inspection accuracy.

3.3.2. Infrared thermography technology

Infrared thermography is suitable for detecting quality issues such as hollow spaces and looseness in riveted nodes. Its basic principle is based on the difference in thermal resistance between normal and defective areas in the riveted region, which is detected using an infrared thermal imager. If rivet looseness leads to local poor contact, the thermal resistance of the defective area will increase, and temperature anomalies will be clearly visible on the thermal image. During specific inspections, inspectors should adopt the following operational techniques:
(1) Calibrate the infrared thermal imager reasonably before inspection to ensure its temperature measurement accuracy;
(2) Select the inspection timing reasonably according to the ambient temperature at the inspection site to prevent interference from direct sunlight and other factors on the inspection results;
(3) During detection, thermal excitation can be applied through cooling or heating to create a significant temperature contrast between normal areas and defective areas. Meanwhile, the intensity of thermal

excitation should be reasonably controlled to avoid causing damage to the components. Additionally, thermal images should be analyzed in conjunction with the specific characteristics of the riveted structure to exclude the influence of temperature differences caused by uneven material distribution in the riveted structure [8].

3.3.3. Ultrasonic testing technology

Ultrasonic testing technology is applicable for detecting quality issues such as internal holes and cracks in riveted joints. During testing, it is necessary to select probes reasonably based on the size of the rivets, typically using straight or angle probes. The connection areas between rivets and components should be prioritized as key inspection zones, and quality defects should be analyzed based on changes in echo signals [9]. At the same time, attention should be paid to grinding the surface of the rivets in advance to ensure they are sufficiently flat, so as not to affect ultrasonic transmission and ensure testing accuracy [10].

4. Conclusion

In summary, for connection joints in steel structure bridges, common detection techniques during connection quality inspection include magnetic particle, ultrasonic, radiographic, visual, torque, tapping, and infrared thermal imaging testing. In practical applications, inspectors should combine multiple techniques in a coordinated manner based on specific circumstances to ensure testing accuracy and promptly identify and resolve quality issues in connection joints.

Disclosure statement

The author declares no conflict of interest.

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