Article

Characteristics of Corrosion Products of Friction-Type High-Strength Bolted Joints of Steel Bridge: A Case Study

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Abstract: The contact surface corrosion of friction high-strength bolt (FHSB) joints was analyzed to examine the characteristics of corrosion products and influence factors in steel bridges. Samples were selected from the Dongying Shengli Yellow River Bridge, which has been in service for 33 years. Scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) were utilized to analyze the microscopic morphology and chemical composition of the corroded surface of the samples. The study identifies that construction quality issues accelerate corrosion of the contact surface and that the contact surface of the aluminum spraying layer transforms from rugged and dense to smooth and porous as corrosion increases. The findings also suggest that the friction coefficient of the FHSB connection node initially decreases and then increases as the corroded surface changes. Corrosion products contained S, Cl, Mn, Si, FeS, and their oxides, indicating that atmospheric, industrial, and Yellow River soil environments contribute to joint corrosion. The study proposes sandblasting and coating the corroded contact surface and deck steel plate with inorganic zinc-rich paint to prevent media penetration and delay substrate corrosion. Adopting ultra-high-performance concrete (UHPC) as the deck structure is also recommended to reduce top plate tensile stress, deck cracking, and media invasion. This study provides insights into the characteristics and mechanisms of FHSB joint corrosion to aid the maintenance, repair, and protection of steel bridges.

Keywords: steel bridge; connection node; friction type high-strength bolt; corrode; SEM; EDS; XRD

1. Introduction

The friction high-strength bolt (FHSB) connection functions primarily by clamping the connecting plate through the strong clamping force generated by bolt fastening and transferring the shear force perpendicular to the bolt axis through the friction force generated by the indirect contact surface of the connecting plate. FHSB is extensively used in steel structure bridges due to advantages such as high connection strength, simple and convenient construction, and the ability to directly bear dynamic and fatigue loads [1–3]. Compared with other steel bridge components, FHSB connection nodes are more prone to corrosion and deterioration, which is primarily reflected in their inherent structural characteristics and the role of surrounding corrosive media [4–8]. Because of frequent gaps between FHSB connectors of steel bridges, water and gases containing corrosive ions can easily invade node components and cause corrosion. Due to the concealed nature of FHSB joint diseases and the complexity of removing the joints, analysis of corroded joint components is mainly based on laboratory testing. Using X-ray diffraction (XRD), scanning electron microscopy (SEM), electrochemical technology, and alternate dry and wet corrosion testing, many studies have examined the corrosion behavior and rust formation mechanism of steel plates in different atmospheric corrosive environments [9,10]. Air pollutants, potential of hydrogen (pH) value, and wet time greatly influence the formation
of the steel surface protective layer [11,12]. For high-strength bolts, a study by Daniel et al. examined the characteristics of corrosion products formed in the contact and exposed areas of bolts and nut fasteners [13]. A study by Wen et al. examined the causes of fracture failure of high-strength bolts of steel bridges in subtropical humid climates, and the results showed that corrosive environment and stress accelerated impact on fracture failure [14]. Compared with industrial atmospheric environments, high-strength bolts showed higher corrosion sensitivity in marine atmospheric environments, which led to bolt loosening and fatigue crack of bolt thread [15,16]. Therefore, the corrosive environment caused severe corrosion behavior in the raw materials of steel bridges, which is one of the main factors affecting the performance degradation of FHSB connection joints of steel structures [17–19]. In an effort to suppress steel corrosion, many researchers have reported various results annually on corrosion inhibitors, including their preparation or extraction, as well as the mechanism of classification and inhibition [20–24]. However, due to the structural characteristics of the FHSB joint and the long-term anti-corrosion requirements, this method still has certain limitations.

In summary, due to the different corrosive environments of FHSB connection nodes of steel bridges, their corrosion behaviors and corrosion products also differ. Therefore, studying the characteristics of corrosion products of nodes on actual bridges and influencing factors in complex environmental corrosive conditions, such as wet, industrial, and dusty climates, is of great value.

This study first analyzed the primary diseases of the FHSB connection nodes of the Dongying Shengli Yellow River Bridge, which has been in operation for 33 years. Then, after selecting seven representative FHSB connection sub-samples and eight steel plate samples, SEM, EDS, and XRD were utilized to analyze the microscopic morphology and chemical composition of corrosion products on the sample surfaces. Finally, this study examines the relationship between the corroded sample surfaces and environmental corrosion, aiming to identify the main causes and propose scientific anti-corrosion protection measures for nodes in aging steel bridges in the future. By clarifying the factors that contribute to corrosion in these structures, this research can help inform the development of effective strategies for preventing corrosion and extending the lifespan of steel bridges.

2. Node Diseases

The Shengli Yellow River Bridge is the first cable-stayed bridge with a steel box girder and orthogonal special-shaped plates built in China. Located in Kenli County, Dongying City, the bridge was completed and opened to traffic in October 1987. With a main bridge span of (60.5 + 136.5 + 288 + 136.5 + 60.5) m, the main beam has 57 steel box sections and 56 transverse joints in total. Its cross-section is a separated double-sided rectangular box. Six orthotropic bridge decks are symmetrically arranged in the middle of the cross-section, with two in upstream and downstream box girders, respectively, and four between the box girders. The top and bottom plates are U-shaped closed ribbed orthotropic plates, most of which are 12 mm thick. Figure 1 shows the schematic diagram of FHSB connection nodes for transverse joints. The transverse joint nodes of the whole bridge are connected by more than 110,000 sets of 10.9 M22 FHSB, and the diameter of the bolt opening is 24.5 mm. The seam between the steel box sections is 6 mm wide, and the splice plate is 10 mm thick. The design value of the friction coefficient of the aluminum spraying contact surface is 0.45, and the longitudinal joint connection is field groove welding. The pavement is composed of an epoxy resin coal tar anti-skid layer, a 40 mm bottom layer, and a 30 mm surface layer of rubber asphalt. Figure 2 shows the schematic diagram of the components of the FHSB connection node.
Figure 1. Schematic diagram of transverse joint FHSB connection node.

Figure 2. Schematic diagram of components of FHSB connection node.

Figure 3 displays some typical diseases of the transverse joint FHSB connection node. Due to exposure of the top plate of the box girder at the lower-part sidewalk and cracking of the pavement, the nodes were corroded by rain and corrosive gas year-round, resulting in severe corrosion of the nodes, with some nut thicknesses reduced by up to 65%. In addition, the longitudinal ribs of the top and bottom plates at the FHSB nodes of the transverse joints had open butt welds, severely weakening the rigidity of the bridge deck, and resulting in different polishing degrees among the joint connecting components. The primary diseases of FHSB connection nodes of transverse joints included coating peeling, corrosion of connection components, and polishing of section plate joints and bolt holes. Investigation and analysis found that 9.62% of bolt holes were not expanded according to specifications. Some gusset plate bolt holes were polished around, generally in a circle of the varying area with an average diameter of 11 mm. Polished bolt holes accounted for 15.22% of the total. Construction quality issues such as nonstandard hole expansion, staggered slab joints, and contact surface pollution led to poor tightness of FHSB connection joint contact surfaces, accelerating corrosion of joint contact surfaces.
In order to examine the surface characteristics of the FHSB connection node assembly, fifteen representative samples at different positions of the node were selected. Table 1 describes the sample material, sampling location, and surface corrosion degrees. A total of seven samples were selected from the surface of the high-strength bolt connection pair, with three (Head-1~Head-3) from the bolt head, two nuts (Nut-1 and Nut-2), and two gaskets (Washer-1 and Washer-2). Among these samples, three (Head-1, Nut-1, and Nut-2) were in direct contact with the atmosphere, two (Head-2 and Head-3) were in contact with the gasket, and two (Washer-1 and Washer-2) were in contact with the upper splice plate. A total of eight samples were selected from the surface of the connecting steel plate assembly, with two (Plate-1 and Plate-2) from the contact surface of the lower splice plate, five (Plate-3~Plate-7) from the contact surface of the upper splice plate, and one (Plate-8) from the contact surface of the roof. Among these samples, five (Plate-1, Plate-2, and Plate-4~Plate-6) were in contact with the roof, and three (Plate-3, Plate-7, and Plate-8) were in direct contact with the atmosphere. Notably, six samples (Plate-1~Plate-6) were primarily used to examine the characteristics of corrosion products of aluminum-sprayed steel plate contact surfaces with different corrosion degrees. In Table 1, the solid samples include Head-2~3, Washer-1~2, Plate-1~5 and Plate-7, the powder samples include Head-1, Nut-1~2, Plate-6 and Plate-8. The materials used for the screw and steel plate in this study were 40B and 16Mnq, respectively. These materials are known as SWRCHB and SM50-B.C in Japan, 50B40 for bolt heads in the United States, and 38B and ST52-3 in Germany [25–27]. The legend for the sample selection positions can be found in Figure 4.
Table 1. Description of sample material, sampling location, and surface corrosion degrees [25–27].

<table>
<thead>
<tr>
<th>Joint Components</th>
<th>Specimen ID</th>
<th>Material Selection</th>
<th>Position</th>
<th>Contact Medium</th>
<th>Description of Surface Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>FHSB connection pair</td>
<td>Head-1</td>
<td>40B Bolt head</td>
<td>Atmosphere</td>
<td>Washer</td>
<td>With the anti-corrosion coating falling off, the surface is slightly rusted and red. No rust is found by naked eye, and local parts are polished and shiny.</td>
</tr>
<tr>
<td></td>
<td>Head-2</td>
<td>45 Nut</td>
<td>Atmosphere</td>
<td>Washer</td>
<td>No rust is found by naked eye, and local polishing is shiny, with obvious boundary.</td>
</tr>
<tr>
<td></td>
<td>Head-3</td>
<td>Washer</td>
<td>Upper splice plate</td>
<td>Atmosphere</td>
<td>Slightly rusted, partially polished, and shiny.</td>
</tr>
<tr>
<td></td>
<td>Nut-1</td>
<td>Nut</td>
<td>Upper splice plate</td>
<td>Atmosphere</td>
<td>The outer layer of the nut is severely rusted and reddish brown.</td>
</tr>
<tr>
<td></td>
<td>Nut-2</td>
<td>45</td>
<td>Upper splice plate</td>
<td>Atmosphere</td>
<td>The inner layer of the nut is severely rusted and brown-black.</td>
</tr>
<tr>
<td></td>
<td>Washer-1</td>
<td>Washer</td>
<td>Upper splice plate</td>
<td></td>
<td>No rust is found with naked eye, and there is obvious boundary.</td>
</tr>
<tr>
<td></td>
<td>Washer-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plate-1</td>
<td>16Mnq Lower splice plate</td>
<td>Roof</td>
<td></td>
<td>No rust is found by naked eye, and the aluminum coating is shiny. The aluminum coating is slightly rusted and gray.</td>
</tr>
<tr>
<td></td>
<td>Plate-2</td>
<td></td>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel plate</td>
<td>Plate-3</td>
<td></td>
<td>Atmosphere</td>
<td></td>
<td>The aluminum spraying layer is severely rusted and reddish brown.</td>
</tr>
<tr>
<td></td>
<td>Plate-4</td>
<td>16Mnq Upper splice plate</td>
<td>Roof</td>
<td></td>
<td>The aluminum spraying layer is severely rusted and reddish brown. The aluminum coating is slightly rusted and gray.</td>
</tr>
<tr>
<td></td>
<td>Plate-5</td>
<td></td>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plate-6</td>
<td></td>
<td>Roof</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plate-7</td>
<td></td>
<td>Atmosphere</td>
<td></td>
<td>With the anti-corrosion coating falling off, the surface is slightly rusted, and red.</td>
</tr>
<tr>
<td></td>
<td>Plate-8</td>
<td>Top plate</td>
<td>Atmosphere</td>
<td></td>
<td>Severely rusted, and brown-black.</td>
</tr>
</tbody>
</table>

Figure 4. Cont.
The instruments utilized in this analysis included a ZEISS SIGMA 500 field emission scanning electron microscope (SEM) from ZEISS, Oberkochen, Germany, which was used to observe the surface morphology of the samples and analyze the chemical composition of both the substrate and corrosion layer using energy spectrum. The material structure of the corrosion products was analyzed using a German D8 ADVANCE A25 X-ray powder diffractometer, Bruker, Billerica, MA, USA. The powdery substances were ground into a fine powder of less than 200 mesh in an agate mortar and placed on the sample tank for testing, while the measured surface of blocky substances was made as flat and smooth as possible to ensure that the sample could be loaded into the \( \varphi 25 \text{ mm} \times 3 \text{ mm} \) sample tank. The wire-cutting machine used was a Hai DK7735 from Changwei, Jiangsu, China, with an average cutting speed of 60–90 mm\(^2\)/min. An ultrasonic cleaner (Model: Xinzhi-SB-5200DT, Xinzhi, Ningbo, China) with a power of 360 W was employed, along with an electric thermostatic drier (Model: Shangcheng-101, Shangcheng, Shaoxing, China) with a voltage/power of 220 V/500 W and a temperature range of 10–300 °C. The ZEISS SIGMA 500 field emission SEM had a resolution ratio of 0.8 nm@30 kV STEM, 0.8 nm@15 kV, 1.4 nm@1 kV, and a magnification range of 10–1,000,000×. The X-ray powder diffractometer used was a D8 ADVANCE A25 from Germany, with an angle measurement range of 10–90 degrees, a Cu target, and a scanning speed of 0.2/step [14,28]. Figure 5 shows a schematic diagram illustrating the experimental setup used in the study.

Figure 4. Sample selection position legend.
products on Plate-7's surface and dense massive corrosion products on Plate-8's surface, though with many cracks and obvious delamination.

Figure 6. 

3.2. Micromorphology

Figure 6 displays the microscopic morphology of the sample surfaces. SEM analysis found that the corrosion products on the surface of the bolt head (Head-1) were mostly scaly and loose. The corrosion products on Head-2 were mostly clastic, with a loose structure, smooth local areas, and obvious boundaries. Head-3 had a compact structure, smooth local areas, and obvious boundaries. The corrosion products of Nut-1 and Nut-2 were mainly needle-shaped, as well as scaly and spiky. The micromorphology of the gasket surface was basically similar to that of Head-2 and Head-3. The surface of Plate-1 aluminum spraying layer was uneven and in a dense granular shape, without visible rust. The surface of the Plate-2 and Plate-5 aluminum spray coating was slightly rusted and dark gray, with layered and cracked corrosion products. The Plate-6 aluminum spraying layer was severely rusted, smooth, porous, and had white powder and a loose surface structure. After the aluminum coating on the contact surface was completely corroded, and the steel plate substrate gradually rusted, the corrosion products of Plate-3 and Plate-4 were reddish-brown, mostly massive, and spherical with obvious cracks. The surface protective layer of Plate-7 and Plate-8 in contact with the atmosphere had basically fallen off, with clustered corrosion products on Plate-7's surface and dense massive corrosion products on Plate-8’s surface, though with many cracks and obvious delamination.

Figure 6. Cont.
In general, the micromorphology of the corrosion products on the surfaces of each sample in contact with the atmosphere was relatively rich, related to the complex corrosive environment of the connecting nodes. Debris accumulation occurred near polished areas formed by the contact surface, likely due to fretting and sliding of the connecting nodes. As the corrosion degree increased, the contact surface of the aluminum spray coating on the steel plate gradually changed from an uneven and dense state to a smooth, porous, powdery state. Once the steel plate substrate gradually rusted, the corrosion product became fluffy and cracked red rust. With insufficient oxygen in the plate seam, the rust gradually turned from red to brown, and the surface bonded. Therefore, the uneven “biting” state of the aluminum sprayed steel plate contact surface was constantly changing. It is
deduced that the friction coefficient of the contact surface decreased first and then increased. Furthermore, polishing around the bolt hole likely changed the roughness and bonding state of the uneven contact surface, reducing the friction coefficient of the contact surface.

3.3. Chemical Composition

Table 2 displays the specification values of the main elements in the sample matrix and EDS results of the corroded surfaces and Yellow River soil. The results showed that the elements mainly originated from the sample elements themselves and corrosive ions in the environment. The surface material of the high-strength bolt connection pair sample comprised the primary elements (Fe, O, and C) and minor elements (Mn, S, Mg, Ti, Ca, Al, Si, P, Cl, Zn, K, Na, etc.). The surface material of the steel plate sample comprised the primary elements (Al, Fe, O, and C) and minor elements (Mn, S, Mg, Ti, Ca, Si, P, Cl, Zn, K, Na, etc.). Several elements (S, Mg, Ca, Si, Cl, and Na) were detected on the surfaces of Plate-1P–late-2 and Plate-4–Plate-6 samples. Multiple elements (Mn, Mg, Ca, Al, Cl, K, and Na) were detected on the surfaces of Plate-3, Plate-7, and Plate-8 samples in contact with the atmosphere.

According to the literature, the sample matrix contained minor amounts of elements such as C, Mn, S, Si, and P [25–27]. Dongying is an industrial oil refining city in China that produces large amounts of nitrogen oxides, sulfur dioxide, and chloride ions, resulting in frequent acid rain in this region. Significant amounts of S and Cl were detected in the corrosion products of the samples. The sample corrosion may have been related to atmospheric corrosion (acid rain). Test results showed that the solid suspended particles in the atmosphere around the Dongying Shengli Yellow River Bridge were primarily composed of Mg, Ca, Al, Si, K, and Na, consistent with the elements of Yellow River soil. Therefore, it is speculated that the Mg, Ca, Si, K, and Na elements present in the corrosion products of the samples may have been related to the inclusion of Yellow River soil.

3.4. Phase Analysis

Figure 7 displays the XRD pattern of corrosion products on the sample surfaces. Analysis results showed that the corrosion products of the bolt head, nut, gasket, and outer surface of the steel plate were primarily iron and silicon oxides. Additionally, the corrosion products of Head-1 contained FeS. Those of Nut-1 and Nut-2 contained MnO₂ and FeOOH. Those of Plate-7 and Plate-8 contained MnO₃ and FeOOH. The corrosion products of the steel plate contact surface samples were primarily aluminum and iron oxides, mostly Al₂O₃, Fe₂O₃, and Fe₃O₄.
Table 2. Specification values of main elements in the sample matrix and the EDS results of surface corrosion products and Yellow River soil [25–27].

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fe</th>
<th>O</th>
<th>C</th>
<th>Mn</th>
<th>S</th>
<th>Mg</th>
<th>Ti</th>
<th>Ca</th>
<th>Al</th>
<th>Si</th>
<th>P</th>
<th>Cl</th>
<th>Zn</th>
<th>K</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>0.37–0.44</td>
<td>0.60–0.90</td>
<td>0.20–0.40</td>
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<tr>
<td>Head-1</td>
<td>52.79–93.69</td>
<td>3.33–38.84</td>
<td>1.70–9.43</td>
<td>0.41–0.75</td>
<td>0.13–0.55</td>
<td>0.36–0.72</td>
<td>0.16–0.34</td>
<td>0.08–1.10</td>
<td>0.20–1.05</td>
<td>0.11–0.28</td>
<td>0.24–0.36</td>
<td>1.11–2.37</td>
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<tr>
<td>Head-2</td>
<td>41.29–86.89</td>
<td>32.62–34.31</td>
<td>11.21–18.07</td>
<td>0.67–0.83</td>
<td>0.19–0.38</td>
<td>0.27–0.32</td>
<td>0.25–0.94</td>
<td>0.23–1.70</td>
<td>0.37–2.90</td>
<td>0.26–2.62</td>
<td>2.34–2.53</td>
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<tr>
<td>Head-3</td>
<td>48.62–64.35</td>
<td>10.40–32.18</td>
<td>8.14–22.56</td>
<td>0.45–0.58</td>
<td>0.28–1.30</td>
<td>0.25–0.34</td>
<td>0.94–1.95</td>
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<tr>
<td>Standard</td>
<td>0.42–0.50</td>
<td>0.50–0.80</td>
<td>≤0.04</td>
<td>0.17–0.37</td>
<td>≤0.04</td>
<td>0.14–0.37</td>
<td>0.38–0.51</td>
<td>0.85–2.54</td>
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<tr>
<td>Nut-1</td>
<td>54.96–60.08</td>
<td>36.40–37.27</td>
<td>2.97–5.71</td>
<td>0.55–1.80</td>
<td>0.15–0.27</td>
<td>0.17–0.24</td>
<td>0.13–0.21</td>
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<tr>
<td>Nut-2</td>
<td>57.11–63.11</td>
<td>32.79–37.14</td>
<td>3.69–5.01</td>
<td>0.41–0.74</td>
<td>0.14–0.32</td>
<td>0.17–0.37</td>
<td>≤0.04</td>
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</tr>
<tr>
<td>Standard</td>
<td>0.42–0.50</td>
<td>0.50–0.80</td>
<td>≤0.04</td>
<td>0.12–0.35</td>
<td>≤0.04</td>
<td>0.13–0.53</td>
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<tr>
<td>Washer-1</td>
<td>6.01–26.69</td>
<td>14.23–28.51</td>
<td>53.50–54.51</td>
<td>0.23–1.38</td>
<td>0.51–0.86</td>
<td>0.87–2.61</td>
<td>0.53–2.37</td>
<td>0.57–1.87</td>
<td>0.42–1.75</td>
<td>0.39–1.99</td>
<td>0.11–1.46</td>
<td>0.30–0.40</td>
<td>0.46–1.28</td>
<td></td>
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</tr>
<tr>
<td>Washer-2</td>
<td>14.89–25.26</td>
<td>17.53–24.53</td>
<td>44.43–56.46</td>
<td>0.39–0.79</td>
<td>0.26–0.54</td>
<td>0.28–2.32</td>
<td>3.01–4.56</td>
<td>0.76–2.29</td>
<td>0.13–0.53</td>
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</tr>
<tr>
<td>Standard</td>
<td>≤0.20</td>
<td>1.20–1.35</td>
<td>≤0.004</td>
<td>1.20–1.35</td>
<td>≤0.015</td>
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<tr>
<td>Plate-1</td>
<td>3.51–3.99</td>
<td>3.93–5.86</td>
<td>0.18–0.64</td>
<td>88.09–90.05</td>
<td>0.35–0.84</td>
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<tr>
<td>Plate-2</td>
<td>6.52–15.62</td>
<td>7.92–21.21</td>
<td>1.64–4.30</td>
<td>0.44–0.65</td>
<td>0.08–0.13</td>
<td>1.25–2.00</td>
<td>11.31–42.51</td>
<td>2.76–3.61</td>
<td>0.73–1.12</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Plate-3</td>
<td>42.42–88.59</td>
<td>7.19–46.19</td>
<td>2.87–6.27</td>
<td>0.24–0.31</td>
<td>0.32–1.43</td>
<td>0.37–1.75</td>
<td>0.98–5.13</td>
<td>0.83–1.29</td>
<td></td>
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</tr>
<tr>
<td>Plate-4</td>
<td>25.16–56.62</td>
<td>23.88–35.11</td>
<td>4.64–5.63</td>
<td>0.61–2.34</td>
<td>0.42–0.94</td>
<td>0.41–0.84</td>
<td>1.32–2.41</td>
<td>1.20–3.24</td>
<td>0.58–1.17</td>
<td>0.78–1.77</td>
<td>0.78–1.37</td>
<td>0.53–1.95</td>
<td>0.99–4.99</td>
<td>0.56–2.03</td>
<td></td>
</tr>
<tr>
<td>Plate-5</td>
<td>0.85–4.95</td>
<td>34.38–54.53</td>
<td>4.71–10.83</td>
<td>0.16–0.61</td>
<td>0.29–0.79</td>
<td>0.15–0.26</td>
<td>0.42–3.45</td>
<td>5.10–39.09</td>
<td>0.34–2.02</td>
<td>0.12–0.16</td>
<td>1.24–3.65</td>
<td>0.28–1.16</td>
<td>0.13–4.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate-6</td>
<td>54.33–62.83</td>
<td>4.61–7.49</td>
<td>0.57–0.81</td>
<td>1.88–2.35</td>
<td>26.74–36.72</td>
<td>0.26–1.42</td>
<td></td>
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<tr>
<td>Plate-7</td>
<td>67.81–87.48</td>
<td>7.94–26.31</td>
<td>1.36–3.48</td>
<td>0.43–1.40</td>
<td>0.18–0.22</td>
<td>0.17–1.27</td>
<td>0.35–1.64</td>
<td>0.35–2.36</td>
<td>0.67–1.62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate-8</td>
<td>61.56–80.96</td>
<td>16.52–32.86</td>
<td>1.82–4.34</td>
<td>0.60–1.73</td>
<td>0.10–0.82</td>
<td>0.15–0.21</td>
<td>1.42–3.05</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>0.96–2.08</td>
<td>43.31–51.02</td>
<td>8.84–10.95</td>
<td>0.36–0.53</td>
<td>0.36–3.29</td>
<td>0.84–1.50</td>
<td>23.62–32.84</td>
<td>0.41–4.33</td>
<td>2.24–4.62</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>
Figure 7. The XRD pattern of sample.

Table 3 displays the XRD results of the primary corrosion products on the sample surfaces. As shown in the table, the corrosion products of most steel plate contact surface samples were Al₂O₃. Fe₂O₃ and Fe₃O₄ were also detected in severely corroded samples. When the corrosive ions, oxygen, water, and dust invaded the joint, the aluminum layer on the joint contact surface was sprayed for oxidation first, and white powder gradually formed as the block fell off. The corrosion product was primarily Al₂O₃. With corrosion of the steel plate substrate, the surface corrosion products were primarily Fe₂O₃ and Fe₃O₄. XRD phase analysis results showed that the samples also contained oxides of Mn, Si, and other elements, as well as FeS. It is speculated that node corrosion was also related to atmospheric (acid rain) and industrial dust and other corrosive environments. Additionally,
the XRD pattern of silty yellow soil showed that SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$ were the primary oxide components, and nearly all samples detected the SiO$_2$ component of Yellow River soil. Because silty yellow river soil was easily adsorbed onto node components after being blown up, the wet yellow river environment year-round may have accelerated node corrosion.

Table 3. XRD results showing the main corrosion products present on the surface of the sample.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Contact Medium</th>
<th>Products</th>
<th>This Study</th>
<th>Ref. [9]</th>
<th>Ref. [28]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>Atmosphere</td>
<td>Fe$_2$O$_3$, FeS, SiO$_2$</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Nut</td>
<td>Atmosphere</td>
<td>Fe$_2$O$_3$, MnO$_2$, FeOOH, SiO$_2$</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Washer</td>
<td>Interface</td>
<td>Fe$_2$O$_3$, Fe$_3$O$_4$, SiO$_2$</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Plate</td>
<td>Interface</td>
<td>Al$_2$O$_3$, Fe$_3$O$_4$, SiO$_2$</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>Atmosphere</td>
<td>Al$_2$O$_3$, Fe$_2$O$_3$, Fe$_3$O$_4$, Mn$_2$O$_3$, FeOOH, SiO$_2$</td>
<td>Fe$_2$O$_3$, Fe$_3$O$_4$, FeOOH</td>
<td>Fe$_3$O$_4$, FeOOH</td>
<td>Fe$_3$O$_4$, FeOOH</td>
</tr>
</tbody>
</table>

Moreover, this study is in agreement with earlier studies (Refs. [9,28]) that attribute the corrosion of FHSB joints to electrochemical processes. Table 3 shows that the samples contained SiO$_2$, Mg, Ca, K, Na, and other elements that are typical components of Yellow River soil. This indicates that the aging and cracking of the asphalt pavement and anti-slip layer are the main paths for corrosive agents and Yellow River soil to penetrate the FHSB joints. To prevent such infiltration, the bridge deck structure should be modified. Construction issues, such as non-standard hole expansion, staggered segmental plate joints, and surface pollution, can also lead to inadequate tightness of the FHSB joint contact surfaces, thereby accelerating corrosion.

4. Corrosion Causes and Prevention

4.1. Corrosion Causes

Pavement design and joint construction quality play a significant role in the corrosion of FHSB joints. Almost all samples detected SiO$_2$ from Yellow River soil, as well as elements such as Mg, Ca, K, and Na, which are consistent with the composition of Yellow River soil. The deterioration and cracking of asphalt pavement and anti-slip layers enable corrosive media and soil to infiltrate the joints. Construction issues such as improper hole expansion, misaligned segmental plates, and contaminated contact surfaces reduce the tightness of the joints, accelerating corrosion. Pavement design and joint construction quality play a significant role in the corrosion of FHSB joints. Almost all samples detected SiO$_2$ from Yellow River soil, as well as elements such as Mg, Ca, K, and Na (Table 2), which are consistent with the composition of Yellow River soil. The deterioration and cracking of asphalt pavement and anti-slip layers enable corrosive media and soil to infiltrate the joints. Construction issues such as improper hole expansion, misaligned segmental plates, and contaminated contact surfaces reduce the tightness of the joints, accelerating corrosion.

The analysis of the Yellow River soil holds significant value as it allows us to gain insights into its composition and its infiltration into the FHSB board joints. The presence of SiO$_2$, observed in most specimens, is particularly noteworthy as it strongly supports the aforementioned conclusion. However, the compounds identified in the Yellow River soil align closely with the main compounds found in the FHSB joint specimen of the node plate. This suggests that only a small fraction of the compound composition and elements can be attributed to the invasion of the Yellow River soil, while the majority are formed as a result of electrochemical corrosion within the specimen itself.

In the early stages of corrosion, specimens in direct contact with the atmosphere form Fe (II) hydrate complexes due to the presence of abundant corrosive H$^+$ in the acid rain environment. This substance is oxidized by dissolved oxygen in water, eventually forming FeOOH. In the later stages, the reaction between FeOOH and Fe$^{2+}$ generated by the anodic reaction results in the formation of a significant amount of brown corrosion product Fe$_3$O$_4$. The surface gradually transitions from a wet to a dry state during sunlight...
exposure, and because FeOOH is an electrochemically active substance, some cluster-like corrosion products FeOOH are prone to dehydration, forming brownish-black products Fe$_2$O$_3$. As a result, flake-like corrosion products appear on the outer structure of the corrosion products. The electrochemical corrosion process on the surface of the aluminum spray layer occurs by conducting electricity outside the water film, internal and external ions, and the aluminum alloy matrix, forming an electrochemical circuit. This leads to corrosion of the aluminum spray layer and ultimately generates Al$_2$O$_3$. The anodic chemical reaction is $\text{Al} - 3e^- \rightarrow \text{Al}^{3+}$, and the cathode is $\text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^-$. The longer the aluminum alloy is covered by a water film in a humid air environment, the more severe the corrosion becomes due to the extended corrosion reaction time.

4.2. Corrosion Prevention

The bridge employs inorganic zinc-rich paint spraying after sandblasting the corroded joint contact surface and bridge deck plate, as it offers superior adhesion and anti-slip friction coefficient compared to the aluminum spraying process. The use of highly metallic zinc as the joint allows the matrix iron to be protected from corrosion due to its high potential; furthermore, the corrosion products of zinc have a dense structure and deposit in the coating’s pores, which can block and seal the pores, preventing the penetration of corrosive media, reducing iron corrosion, and improving the friction coefficient of the contact surface. Additionally, the bridge deck reinforcement uses UHPC as the structural layer to participate in the joint stress, significantly reducing the tensile stress of the box girder top plate and minimizing the risk of UHPC bridge deck cracking and corrosion medium invasion.

Consequently, the primary steps of the corroded FHSB joints repair and bridge deck reinforcement construction process are as follows: milling the original pavement layer → removing bolt groups → sandblasting the contact surface → spraying inorganic zinc-rich paint → re-bolting the splicing plate → overall sandblasting and rust removal of the steel bridge deck → spraying inorganic zinc-rich paint → welding shear nails and arranging steel bars → paving a 55 mm thick UHPC bridge deck and 30 mm thick asphalt concrete.

5. Conclusions

This study investigated the characteristics and influencing factors of corrosion products in FHSB connection joints. First, the primary damage modes of joints in the Dongying Shengli Yellow River Bridge were analyzed. Then, seven representative FHSB connection sub-samples and eight steel plate samples were selected. Scanning electron microscopy, energy dispersive spectroscopy, and X-ray diffraction were used to analyze the microscopic morphology and chemical composition of corrosion products on the sample surfaces. Finally, the relationship between corrosion products and environmental corrosion was discussed. The main findings are as follows:

1. After the aluminum coating corroded, the contact surface changed from uneven and dense to smooth and powdery. As the steel substrate corroded further, the contact surface transformed from fluffy and stratified to surface-bonded. These changes in the corroded contact surface significantly impacted the slip-bearing capacity of the FHSB joint by altering the friction coefficient;
2. Almost all samples detected SiO$_2$ from Yellow River soil as well as elements such as Mg, Ca, K, and Na, largely matching Yellow River soil composition. Cracking of asphalt pavement and anti-slip layers allowed corrosive media and soil to invade the joints. Joint tightness was impaired by construction issues, accelerating corrosion;
3. Corrosion products contained large amounts of S and Cl as well as oxides of Mn, Si, and other elements and FeS, indicating atmospheric corrosion (e.g., acid rain) and industrial dust contributed to joint corrosion;
4. Sandblasting and coating the corroded contact surface and deck steel plate with inorganic zinc-rich paint prevented media penetration and delayed substrate corrosion.
Adopting UHPC as the deck structure reduced top plate tensile stress, deck cracking, and media invasion.

Going forward, corrosion behavior and mechanisms in simulated environments will be examined to propose methods to delay corrosion rates and extend joint service life. The effects of corrosion on friction coefficients and clamping forces will be studied to reveal joint anti-slip force degradation mechanisms.

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