Corrosion fatigue of welded joints of steel for marine platform

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Experiments on the corrosion fatigue behaviour of welded joints of the steel for marine platform in air and seawater, and of the joints in seawater with cathodic protection, yielded data for linear regression to obtain fatigue life curves ($\Delta S$-$N_f$). The laws of corrosion fatigue in welded joints of test steel are discussed with reference to those of A587 and A131 steel. In these experiments, the fatigue damage occurring at all welded joints around the weld interface resulted in the cracks and fractures. The fatigue life of the specimens in seawater with cathodic protection is longer than that in seawater without protection.

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With the rapid development of offshore petroleum exploitation, many stationary tubular offshore steel structure platforms have been designed and constructed in China. They were subjected to cyclic loading in marine environment. The combined action of cyclic loading and harsh environment often resulted in significantly lower fatigue performance compared with that under cyclic loading condition in mild environment. Corrosion fatigue might be a simple resultant of fatigue cracking and corrosive attack or it might be a more complex synergistic interaction of these two processes. In steel-structured offshore platforms of welded steel components, such as steel tubes, plates, and angle irons, most corrosion fatigue cracking occurred around the weld interface in the welded region, where residual welding stress, welding fault and geometrical defect exist and are focused on. Study of the corrosion fatigue performance of steel plates for offshore platform in air, seawater and in seawater with cathodic protection yielded data on the corrosion fatigue life of steel (in different zone and in different protective conditions on an offshore platform) for possible theoretical reference for design and selection of offshore platform.

Materials and Methods

Materials

Test steel plates (18 mm thick) provided by the Shipbuilding Factory in Rongcheng City were used on an offshore platform of the Shengli Oil Field. Its chemical composition and mechanical properties are listed in Tables 1 and 2.

Table 1—Chemical composition of the test steel

<table>
<thead>
<tr>
<th>Elements</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Content(%)</td>
<td>0.19</td>
<td>0.27</td>
<td>0.86</td>
<td>0.021</td>
</tr>
</tbody>
</table>

Table 2—Mechanical properties of the test steel

<table>
<thead>
<tr>
<th>$\sigma_y$ (N/mm$^2$)</th>
<th>$\sigma_b$ (N/mm$^2$)</th>
<th>$\sigma$ (%)</th>
<th>$Ak_{so}$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>360</td>
<td>520</td>
<td>31</td>
<td>33</td>
</tr>
</tbody>
</table>

1. $\sigma_y$: yielding limit of steel plate, 2. $\sigma_b$: tensile strength, 3. $\sigma$: stretch rate, 4. $Ak$: V gap (10×10 mm) lash work

Butt-welded plates were adopted. Steel plates (18 mm thick, 72.5 mm wide) were butt-welded as specimens in order to simulate practical one-leg platform structure (Fig. 1). As these welded specimens had not been used after qualification test, they remained in their original state. In this experiment, the reference specimens A537 and A131 steel were also butt-welded plates samples.

Methods

In the experiment, four-point bending cyclic loading system (Fig. 2) was adopted to obtain high stress with minimal loading, to simulate the bending stress state of the hot spot of tubular joints on a
platform. The maximum surface stress of the bending state of the specimens in the four-point bending cyclic loading system was measured by a couple of strain gauges on the two up-and-down sides of the steel plate distancing about 25 mm from the weld toe, and at the central line of the two right-and-left sides of the transverse clapboard of the specimens. In the condition of the cyclic loading, the stress range (ΔS) could be obtained by multiplying stress range (Δε) measured by the strain gauges by the elastic modulus of the steel (E=2.16×10^5 N·mm\(^{-2}\)). The additional loading was conformed by the stress reading, then the cyclic loading test controlling the loading was carried out.

To simulate the low frequency cyclic loading of waves, the cyclic loading frequency in this experiment was 0.5 Hz, and stress ratio (R) was -1.

Experiments on the corrosion fatigue in air, seawater and in seawater with cathodic protection respectively were made to study the effects of seawater corrosion on fatigue properties.

Artificial seawater was used in a seawater circulation system (according to ASTMD1141-75 direction). Seawater from a plastic seawater pool surrounding the welded gap, was made to flow continuously over the local surface of the welded gap. Tables 3 and 4 list the compositions and parameters of the seawater.

Electrical current from a potentiostat provided cathodic protection. In accord with the normal requirement of offshore platform, the cathodic potential of samples was set at -850 mV (vs. SCE). Platinum silk encircling the Lucite glass surrounding the welded gap of the samples acted as cathode.

**Results and Discussion**

In all of the experiments, specimens that had weld joints suffered fatigue damage on weld toe, the weld interface at the intersection of the welded part and original material, which resulted in the occurrence of a seam and resulting fracture. Geometrical shape had decisive effects on welding steels. Corrosion fatigue fracture was often induced at the edge of a welded beam where residual stress and gaps existed. Besides the pure gap effect, the welding operation also made the metallurgy composition of this region different from that of the original material\(^{2,3}\). The intensity of corrosion fatigue of the weld joints was determined by the stress level at the weld interface. The experiment was aimed to determine the relationship between maximum stress range (ΔS) in bending stress state and the loading cycle (N\(_f\)) of fatigue induced crack on the weld interface. The dependence of ΔS on N\(_f\) usually appear in linear relation in a right-angle logarithmic coordinate system, and can be expressed by the equation.

\[
\lg \Delta S = a + b \lg N_f \quad \ldots (1)
\]

The fatigue experiment data were analyzed by linear regression in a right-angle logarithmic coordinate system to obtain the ΔS-N\(_f\) relationship curves reflecting the average fatigue life of the welded steel.

The surface bending stress under the four-point bending cyclic loading could be calculated by the follow equation.

\[
S = \frac{6pl}{bh^2} = \frac{3pl}{bh^2} \quad \ldots (2)
\]

p is the fulcrum loading, P = 2p, the additional loading, l the fulcrum distance, b the plate width, h the plate thickness (Fig. 3).

| Table 3 — Compositions of seawater (g/L) |
| NaCl          | 24.53 |
| MgCl\(_2\)    | 5.20  |
| Na\(_2\)SO\(_4\) | 4.09 |
| CaCl\(_2\)    | 1.16  |
| KCl           | 0.695 |
| Na\(_2\)CO\(_3\) | 0.201 |
| KBr           | 0.101 |
| H\(_3\)BO\(_3\)) | 0.027 |
| SrCl\(_2\)    | 0.025 |
| NaF           | 0.003 |

Note: According to ASTMD1141-75 direction

<p>| Table 4 — Parameters of seawater |</p>
<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>pH</th>
<th>Salinity (mg/L)</th>
<th>Chlorinity (mg/L)</th>
<th>Oxygen content (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-21</td>
<td>7.5-8.5</td>
<td>32-36</td>
<td>18.20</td>
<td>11-12</td>
</tr>
</tbody>
</table>

Fig. 2— Sketch of the four-point bending cyclic loading system (1-sensor, 2-servo mechanism, 3-specimen, 4-seawater trough)
Because of $R = -1$, the stress range $\Delta S = 2S$, then

$$\Delta S = \frac{6Pl}{bh^2} \quad \ldots (3)$$

In this test, $l=280$ mm, $b=72.5$ mm, $h=18$ mm.

Figures 4-6 are the respective $\Delta S-N_f$ curves of the welded steel in air, seawater, and seawater with cathodic protection according to the Eq. (1). The correlation coefficients were $r_{\text{air}}^2$ (meaningless), $r_{\text{sw}}^2=0.957$, and $r_{\text{cp}}^2=0.876$, respectively. In the fatigue experiments in air, two of five welded steel samples did not break even when the loading cycle reached $2 \times 10^6$ in the low stress level experiment at the end of the test. So there were only three sets of experimental data. Although the correlation coefficient $r_{\text{air}}$ was meaningless, the linear relation of the data points was very fine, which showed the experimental data points were not too dispersed.

As the compositions and mechanical properties of the reference A587 and A137 steel samples were similar to those of the tested steel ship plates, and as the experiments on the butt-welded joint samples were done under conditions similar to those for the testing samples, Figs 4-6 show that the difference of the slopes of the average corrosion fatigue life curves in air, seawater, and seawater with cathodic protection respectively was nominal. A587 (25 mm) steel was thicker than the testing steel (18 mm), and so, has much shorter average fatigue life. The average fatigue life of 19 mm thick A131 steel was a little shorter than the 18 mm thick test steels. So we can see that the experimental results were reasonable. The quality (especially welding quality) of the test steels was good.

Figure 7 compares the fatigue life in air, seawater and in seawater with cathodic protection. The $\Delta S-N_f$ curves in the figure show that the fatigue life of freely corroded welded joints in seawater was about 1/2 to 1/3 of that in air, and that the difference between them increased with the decrease of the stress level. Comparison of the samples in seawater, with and without cathodic protection showed that the fatigue-life of the former was longer than that of the latter at high stress level (short life); that the protective effect of the former was better at lower stress level. Comparison of the slopes of the $\Delta S-N_f$ curves under three different conditions showed that the absolute
value of the slope of the corrosion fatigue life in seawater with cathodic protection was the lowest. In fact, the cycling number of sea waves loading was more than $10^7$-$10^8$ during the service time of a platform at sea. So the long-term good effect of cathodic protection ($-850$ mV, SCE) was very obvious. The fatigue life with cathodic protection was even close to that in air. The above accorded with recent years research results obtained in China and abroad.

Cathodic protection to lengthen fatigue life under low stress and long time conditions can be achieved by minimizing the occurrence of local corrosion crack in the stable slippage zone. The protective potential to inhibit corrosion fatigue was about the same as that to inhibit the overall average corrosion. In addition, the presence of calcium carbonate furring was one of the major factors that decreased the occurrence probability of corrosion fatigue crack in seawater. For welded steel joints under low stress for a long time, the fatigue life in the incipient crack and stretching shallow crack stage was often very long. Cathodic protection lengthened greatly the fatigue life of this stage, and obviously lengthened the whole fatigue life. Whereas under high stress (short life), because cathodic protection caused hydrogen bubbles to occur and greatly increased the cracking extension rate, the whole fatigue life shortened.

Conclusions

From this study the following conclusions can be drawn:

(i) In three different media, air, seawater, and in seawater with cathodic protection, the fatigue induced damage to all welded joints occurred around the weld interface and resulted in crack and fracture.

(ii) The dispersion extent of all the fatigue life data was not large, so the experiment results are reliable.

(iii) Comparison of the results of this experiment with those of other experiments showed that the quality (especially welded quality) of welded steel samples was good.

(iv) In average, the corrosion fatigue life of welded joints in seawater was about 1/2 to 1/3 of that in air, the difference between the fatigue life in seawater, and the fatigue life in air was greater with decreased stress level.

(v) At low stress level (long life), the fatigue life of welded joints in seawater with cathodic protection ($-850$ mV, SCE) was longer than the free corrosion fatigue life of welded joints in seawater. With decreasing of stress level, cathodic protection was more effective in lengthening the fatigue life to even close to that in air.

References