The Study on Fatigue Experiment and Reliability Life of Submarine Pipeline Steel

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Abstract: The aim of the fatigue experiment study is to solve the fatigue fracture problem of X70 submarine tubing when it is under the scouring effect of offshore current. The multilevel fatigue experiments are carried out following the international (GB4337-84) recommended method. The standard round bar fatigue specimen was made by the material of submarine pipeline steel. The fatigue life of submarine pipeline steel in different survival probability and P-S-N curve were achieved. According to reliability numerical analysis method, the reliability fatigue life of pipeline steel in different stress level is got. The results show that the fatigue life of X70 submarine pipeline steel obeys the normal distribution. The detection of submarine pipeline scouring condition should be enhanced and the pipeline zone which was scoured seriously should be repaired and controlled effectively in order to reduce the scouring effect of ocean current.

Keywords: Fatigue life, offshore wave scouring, PLG-300C testing machine, P-S-N curve, submarine pipeline

INTRODUCTION

When submarine pipeline transports the oil under the sea, it is also affected by the scouring effect of unstable ocean wave. Fatigue failure will happen when the fatigue strength is beyond the endurance of the pipeline (Dmytraph, 2008; Lee and Kim, 2005; Lee et al., 2008) So it is necessary to predict the fatigue life of the submarine pipeline to make sure it works safely in different stress.

The analysis is based on the X70 pipeline steel. As the pipeline is affected by the cyclic stress under the sea, the fatigue experiment is done by the fatigue-testing machine using the sine wave with frequency 10-40 Hz (Shlyushenkov et al., 1990; Sosnovskii and Vorob’ev, 2000). The fatigue life in different stress scales is shown accordingly. Using the multilevel fatigue loading experiment, the fatigue grouped experimental data of X70 submarine pipeline were obtained in the PLG-300C HF fatigue testing machine. By the parameter estimation and distribution pattern checking of the fatigue life, the parametric distribution law of X70 pipeline steel was obtained. By calculating the linear correlation coefficients of the fatigue probability and its normal quantity, it is confirmed that the fatigue life of X70 pipeline steel satisfies the lognormal distribution. By calculating the correlation coefficients in different survival rate, the P-S-N curves are drawn accordingly to show that the S-N curve has higher linear correlation coefficient when survival rate is higher (Tosha et al., 2008).

Under the specified fatigue life standard, the safety inspection procedure should be established and improved in order to enhance the safety reliability of submarine pipeline engineering. The safety methods should be determined to make the submarine pipeline works normally. Thus the fatigue stress amplitude of the X70 pipeline steel decreases and the engineering life of submarine pipeline can be prolonged.

FATIGUE EXPERIMENT

The specimen is designed by the axial loading smooth cylindrical standard sample according to the national standard (GB4337-84). The specimen is processed by the X70 steel with 560.3×4.8 mm. The scale is: the sectional dimension of the test section is 55×1.5 mm and its sectional length is 70 mm. The radius of rounded curvature is 30 mm. The both ends of the gripping section are 60×4 mm and its length is 70 mm. The total length of the specimen is about 300 mm. To increase the accuracy of the experiment, both inside and outside section are clamped by a special fixture. The experimental section of the specimen is scaled by the five sections with equal intervals. The four points are marked with equal circumference on the circle of every section. To get the more accuracy sectional area, the thickness of the wall is measured in each measuring.
The device of the fatigue experiment is the PLG-300C HF fatigue-testing machine and its corresponding test system. The frequency of the test is 10~40 Hz. The cyclic stress is sin wave with the stress ratio \( r = 0.25 \). The 14 available tests of the three groups are taken in the test. The maximum stress scales are 530.3, 478.4 and 456.8 Mpa, respectively. The test result is shown in Table 1. The fracture status of the test piece is shown in Fig. 2.

The fatigue reliability and P-S-N curve:
The parameter estimate of the fatigue life: According to the topic of the study (Zhai et al., 2003; Gao, 1986), the X70 steel satisfies the lognormal distribution in every stress levels. The fatigue life \( N_i \) of every stress levels can be ranged from the small to the big to get

\[
N_1 \leq N_2 \leq \ldots \leq N_n \leq N_n.
\]

As the logarithm is \( X_i = \lg N_i \), then

\[
X_1 \leq X_2 \leq \ldots \leq X_{n-1} \leq X_n.
\]

The means \( \mu_x \) and the standard deviation of the logarithmic fatigue life are calculated as follow:

\[
\bar{X} = \frac{1}{n} \sum_{i=1}^{n} X_i = \mu_x
\]

\[
S_X = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \bar{X})^2} = \sigma_x
\]

where, \( n \) is the test specimen in different stress level, from the Table 1, \( n = 3-5 \).

The validation on the distribution pattern of the fatigue life: According to the assumption that the fatigue life of the steel follows the lognormal distribution (Nuhi et al., 2011), it needs to validate in order to make the assumption reasonable and the test result available. According to the study, if the logarithmic fatigue life of the test satisfies the lognormal distribution, the logarithmic fatigue life is in linear relation with the corresponding survival rate.

Ranging \( X_i \) in the sequence from small to big (Yang and Chen, 1984), the result is shown in average rank and its corresponding failure probability of the \( X_i \):

\[
F(X_i) = \frac{i}{n+1}
\]

The corresponding survival rate:

\[
P_i = 1 - F(X_i)
\]

In the formula,

\( i \): The serial number of the logarithmic fatigue life in ascending order, \( i = 1, 2 \ldots, n \)

\( n \): The capability of the sample

\( X_i, P_i \): The probability-based logarithmic fatigue life and the corresponding discrete value of survival rates

As the survival rate \( P \) is shown in percentage, it’s not easy to calculate. According to the study, there is

<table>
<thead>
<tr>
<th>Scale of the load</th>
<th>The test number</th>
<th>Max. stress ( \sigma_{max} )/Mpa</th>
<th>Min. stress ( \sigma_{min} )/Mpa</th>
<th>Amplitude ( \sigma_a )/MPa</th>
<th>Avg. stress ( \sigma_m )/MPa</th>
<th>Stress ratio ( r )</th>
<th>Fatigue life ( N_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A1</td>
<td>530.3</td>
<td>132.6</td>
<td>198.9</td>
<td>331.4</td>
<td>0.25</td>
<td>220561</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>239976</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>266595</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>347850</td>
</tr>
<tr>
<td></td>
<td>A5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>498071</td>
</tr>
<tr>
<td>B</td>
<td>B1</td>
<td>478.4</td>
<td>119.5</td>
<td>179.4</td>
<td>298.9</td>
<td>0.25</td>
<td>425067</td>
</tr>
<tr>
<td></td>
<td>B2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>530786</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>685570</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1585571</td>
</tr>
<tr>
<td>C</td>
<td>C1</td>
<td>456.8</td>
<td>114.2</td>
<td>171.3</td>
<td>285.0</td>
<td>0.25</td>
<td>773297</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>908846</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3622186</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3693421</td>
</tr>
<tr>
<td></td>
<td>C5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt;10^7</td>
</tr>
</tbody>
</table>

Max.: Maximum; Min.: Minimum; Avg.: Average
Table 2: The linear correlation coefficients between the fatigue life and normal quantity

<table>
<thead>
<tr>
<th>Stress level</th>
<th>Linear equation</th>
<th>Linear correlation coefficients R</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$X_p = 6.66527 + 0.3034123u_p$</td>
<td>0.97369</td>
</tr>
<tr>
<td>B</td>
<td>$X_p = 5.768810 + 0.3453314u_p$</td>
<td>0.95860</td>
</tr>
<tr>
<td>C</td>
<td>$X_p = 6.33012 + 0.6577299u_p$</td>
<td>0.96230</td>
</tr>
</tbody>
</table>

one-to-one relationship between the survival rate (P) and the normal quantity ($u_p$). So we can use $u_p$ to calculate linear relationship instead of P. The reference study (Zhai et al., 2003) has given the linear equation as follows:

$$X = \log N = a + b \log S$$

From the equation (10), the corresponding S-N curve is:

$$X = \log N = a + b \log S$$

In fact, the steel average fatigue life $X$ from (1) is the logarithmic fatigue life when survival rate is 50%. The equation (10) can be solved by Least square method (Balytskyi et al., 2006; Makarenko et al., 2008):

$$a = \frac{1}{m} \sum_{i=1}^{m} \bar{X}_i - b \frac{\sum_{i=1}^{m} \log S_i}{m}$$

$$b = \frac{\sum_{i=1}^{m} \bar{X}_i \log S_i - \frac{1}{m} \left( \sum_{i=1}^{m} \log S_i \right) \left( \sum_{i=1}^{m} \bar{X}_i \right)}{\left( \sum_{i=1}^{m} (\log S_i)^2 \right) - \frac{1}{m} \left( \sum_{i=1}^{m} (\log S_i) \right)^2}$$

where,

$\bar{X}_i$ : The logarithmic mean value of the fatigue life in stress level $i$

$S_i$ : The stress value of the stress level $i$

$m$ : The stress level of the fatigue test. Here $m = 3$

The fatigue life in any survival rate $P$, can be estimated by the parameters in Eq. (1) and (2) and be solved by the Eq. (14):

$$X_p = \log N_p = a_p + b_p \log S$$

The P-S-N curve of fatigue life in certain survival rate: The fatigue life $N_p$ under different survival rate has the certain relationship with its corresponding cyclic stress (Wirsching and Torng, 1991):

$$X_p = \log N_p = a_p + b_p \log S$$

where,

$a_p$ & $b_p$ : The undetermined coefficients in different survival rate. It is only related to the nature of the material

$\log N_p$ : In linear relationship with $\log S$

$\log N_p$ is the logarithmic fatigue life when survival rate is 50%.
Table 3: The coefficients of P-S-N curve in different survival rate

<table>
<thead>
<tr>
<th>Survival rate (%)</th>
<th>( a_p )</th>
<th>( b_p )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>43.98551</td>
<td>-14.11435</td>
<td>-0.98160</td>
</tr>
<tr>
<td>60</td>
<td>41.23819</td>
<td>-13.51225</td>
<td>-0.98260</td>
</tr>
<tr>
<td>70</td>
<td>38.66657</td>
<td>-12.30454</td>
<td>-0.98380</td>
</tr>
<tr>
<td>80</td>
<td>35.47671</td>
<td>-11.90279</td>
<td>-0.98541</td>
</tr>
<tr>
<td>90</td>
<td>31.53956</td>
<td>-10.43446</td>
<td>-0.98811</td>
</tr>
<tr>
<td>95</td>
<td>26.94149</td>
<td>-8.190780</td>
<td>-0.99080</td>
</tr>
<tr>
<td>99</td>
<td>20.94149</td>
<td>-6.561820</td>
<td>-0.99708</td>
</tr>
<tr>
<td>99.9</td>
<td>14.45663</td>
<td>-3.993560</td>
<td>-0.99352</td>
</tr>
<tr>
<td>99.99</td>
<td>9.544790</td>
<td>-2.590560</td>
<td>-0.99699</td>
</tr>
<tr>
<td>99.999</td>
<td>7.459020</td>
<td>-2.126780</td>
<td>-0.99889</td>
</tr>
</tbody>
</table>

To the linear relationship between \( \dot{X}_{pi} \) and \( S_n \), we use correlation coefficient \( R \) to assess the degree of linear fitting. To this problem, the linear correlation coefficients are (Nazir et al., 2008):

\[
R = \frac{(L_{SN})_p}{\sqrt{(L_{SS})_p(L_{NN})_p}} 
\]

\[
(L_{SN})_p = \sum_{i=1}^{n} (\bar{X}_{pi})(\log S_i) - \frac{1}{m} \left( \sum_{i=1}^{n} \bar{X}_{pi} \right) \left( \sum_{i=1}^{n} \log S_i \right) 
\]

Fig. 3: The P-S-N curve of X70 steel test piece, (a) The P-S-N curve of double logarithmic coordinate, (b) The P-S-N curve of rectilinear coordinates

Fig. 4: Test of distribution type for fatigue life of submarine pipelines, (a) stress level A, (b) stress level B, (c) stress level C

\[
(L_{SN})_p = \sum_{i=1}^{n} (\log S_i)^2 - \frac{1}{m} \left( \sum_{i=1}^{n} \log S_i \right)^2 
\]

\[
(L_{SS})_p = \sum_{i=1}^{n} (\log S_i) \left( \log S_i \right) - \frac{1}{m} \left( \sum_{i=1}^{n} \log S_i \right)^2 
\]
The Table 3 is the undetermined coefficients of different survival rates in Eq. (10). The Fig. 3 is the P-S-N curve of X70 steel test piece which is drawn according to the Table 3. Figure 4 is the test of distribution type for fatigue life in different stress level shown in Table 2.

**CONCLUSION**

The fatigue life distribution pattern and its corresponding P-S-N curve are obtained and we can draw the conclusion:

- The fatigue life of X70 steel satisfies the logarithmic distribution
- The fatigue stress-life curve of X70 steel satisfies the stress-life curve of normal metal
- To the certain fatigue life, we need to reduce the steel stress in certain circumstances to get higher reliability

The P-S-N curve from the experiment only reflects the fatigue state of test piece in the test condition. Due to stress concentration and other condition in reality, the relationship may change in the complex situation. As the fatigue lives in different stress level are obtained, the corresponding safety measures can be made to prevent the occurrence of pipeline crack.

**REFERENCES**


