Research Journal of Applied Sciences, Engineering and Technology 5(5): 1695-1699, 2013
DOI:10.19026/rjaset.5.4925
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: July 24, 2012 Accepted: August 21, 2012 Published: February 11, 2013

Research Article

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

[1]Yan Yifei, [1]Shao Bing, [1]Liu Jinkun and [2]Cheng Lufeng
[1]Department of Electromechanical Engineering, China University of Petroleum Qingdao, Shandong 266580, China
[2]China petroleum Engineering and Construction Corp, Drum Tower Street No.28, Dongcheng District, Beijing 100120, China

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 internation (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 condation 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 pepeline 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 he fatigue life of the submarine pipline 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 sina 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 safefy 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 cylinderical standard sample according to the national standard (GB4337-84). The specimen is processed by the X70 steel with Φ60.3×4.8 mm. The scale is: the sectional dimension of the test section is Φ55×1.5 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

Corresponding Author: Yan Yifei, Department of Electromechanical Engineering, China University of Petroleum Qingdao, Shandong 266580, China

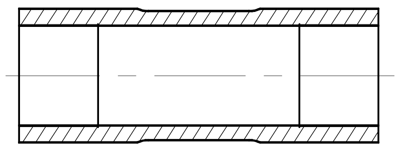

Fig. 1: The structure diagram of the fatigue test piece

Fig. 2: The fracture of the test piece

point. The outer radius is measured by every two points. The structure of the specimen is in Fig. 1.

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 $N_1 \le N_2 \le \ldots\ldots \le N_{n-1} \le N_n$. As the logarithm is X_i = lgN_i, then $X_1 \le X_2 \le \ldots\ldots \le X_{n-1} \le X_n$

The means and the standard deviation of the logarithmic fatigue life are calculated as follow:

$$\overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i = \hat{\mu}_X \tag{1}$$

$$S_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2} = \hat{\sigma}_X \tag{2}$$

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:

$$F\left(X_i\right) = \frac{i}{n+1} \tag{3}$$

The corresponding survival rate:

$$P_i = 1 - F\left(X_i\right) \tag{4}$$

In the formula,

i : The serial number of the logarithmic fatigue life in ascending order, i = 1, 2 …, 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 1: The fatigue testing data of the X70 steel

Scale of the load	The test number	Max. stress σ_{max}/Mpa	Min. stress σ_{min}/MPa	Amplitude σ_a/MPa	Avg. stress σ_m/MPa	Stress ratio r	Fatigue life Ni
A	A1	530.3	132.6	198.9	331.4	0.25	220561
	A2						239976
	A3						266595
	A4						347850
	A5						498071
B	B1	478.4	119.5	179.4	298.9	0.25	425067
	B2						530786
	B3						685570
	B4						1585571
C	C1	456.8	114.2	171.3	285.0	0.25	773297
	C2						908846
	C3						3622186
	C4						3693421
	C5						$>10^7$

Max.: Maximum; Min.: Minimum; Avg.: Average

Table 2: The linear correlation coefficients between the fatigue life and normal quantity

Stress level	Linear equation	Linear correlation coefficients R
A	$\hat{X}_P = 6.66527 + 0.3034123u_p$	0.97369
B	$\hat{X}_P = 5.768810 + 0.3453314u_p$	0.95860
C	$\hat{X}_P = 6.33012 + 0.6577299u_p$	0.96230

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:

$$X_P = lg\, N_P = c + du_P \tag{5}$$

In the formula,
c, d : Undetermined coefficients
u_P : Normal quantity

The linear correlation coefficients of the X_P with the u_P are as follows:

$$R = \frac{L_{u_P X_P}}{\sqrt{L_{X_P X_P} L_{u_P u_P}}} \tag{6}$$

$$L_{u_P X_P} = \sum_{i=1}^{n} u_{Pi} X_i - \frac{1}{n}\left(\sum_{i=1}^{n} u_{Pi}\right)\left(\sum_{i=1}^{n} X_i\right) \tag{7}$$

$$L_{X_P X_P} = \sum_{i=1}^{m} X_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} X_i\right)^2 \tag{8}$$

$$L_{u_P u_P} = \sum_{i=1}^{n} u_{Pi}^2 - \frac{1}{n}\left(\sum_{i=1}^{n} u_{Pi}\right)^2 \tag{9}$$

In different stress level, the linear correlation coefficients between the fatigue life and normal quantity are shown in Table 2.

From the analysis, we know that the logarithmic fatigue life is in linear relationship with the normal quantity u_P. So the assumption that the fatigue life of the pipeline steel satisfies the lognormal distribution is valid.

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):

$$X_P = lg\, N_P = a_P + b_P\, lg\, S \tag{10}$$

where,

a_P & b_P : The undetermined coefficients in different survival rate. It is only related to the nature of the material
lgN_P : In linear relationship with lgS

In fact, the steel average fatigue life $\bar{X}$ from (1) is the logarithmic fatigue life when survival rate is 50%. From the equation (10), the corresponding S-N curve is:

$$X = lg\, N = a + b\, lg\, S \tag{11}$$

When the survival rate is 50%, the value of a_P and b_P, can be calculated by Least square method (Balytskyi *et al*., 2006; Makarenko *et al*., 2008):

$$a = \frac{1}{m}\sum_{i=1}^{m}\bar{X}_i - \frac{b}{m}\sum_{i=1}^{m}\lg S_i \tag{12}$$

$$b = \frac{\sum_{i=1}^{m}\bar{X}_i \lg S_i - \frac{1}{m}\left(\sum_{i=1}^{m}\lg S_i\right)\bullet\left(\sum_{i=1}^{m}\bar{X}_i\right)}{\sum_{i=1}^{m}(\lg S_i)^2 - \frac{1}{m}\left(\sum_{i=1}^{m}\lg S_i\right)^2} \tag{13}$$

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):

$$\bar{X}_P = \bar{X} + u_P S_X \tag{14}$$

where,
$\bar{X}_p$: The mean value of logarithmic fatigue life in any survival rate P

To the fatigue data of the steel test piece which is divided into m level, it also can be solved by least square method:

$$a_P = \frac{1}{m}\sum_{i=1}^{m}\bar{X}_{Pi} - \frac{b_P}{m}\sum_{i=1}^{m}\lg S_i \tag{15}$$

$$b_P = \frac{\sum_{i=1}^{m}\bar{X}_{Pi}\, lg\, S_i - \frac{1}{m}\left(\sum_{i=1}^{m} lg\, S_i\right)\bullet\left(\sum_{i=1}^{m}\bar{X}_{Pi}\right)}{\sum_{i=1}^{m}(lg\, S_i)^2 - \frac{1}{m}\left(\sum_{i=1}^{m} lg\, S_i\right)^2} \tag{16}$$

Obviously, when P = 50%, a = a_P, b = b_P.

Table 3: The coefficients of P-S-N curve in different survival rate

Survival rate (%)	a_P	b_P	R
50	43.98551	-14.11435	-0.98160
60	41.23819	-13.51225	-0.98260
70	38.66657	-12.30454	-0.98380
80	35.47671	-11.90279	-0.98541
90	31.53956	-10.43446	-0.98811
95	26.39541	-8.190780	-0.99080
99	20.94149	-6.561820	-0.99708
99.9	14.45663	-3.993560	-0.99352
99.99	9.544790	-2.590560	-0.99699
99.999	7.459020	-2.126780	-0.99889

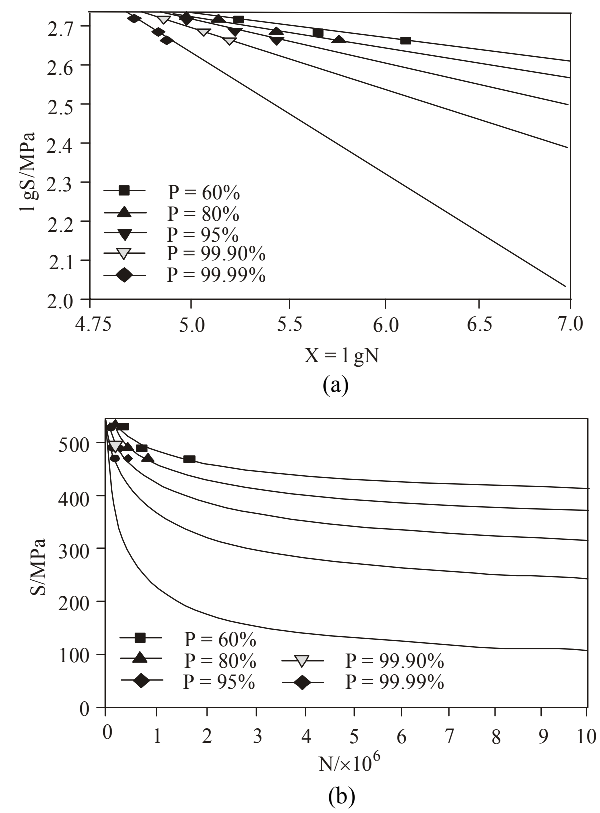

Fig. 3: The P-S-N curve of X70 steel test piece, (a) The P-S-N curve of double logarithmic coordinate, (b) The P-S-N curve of rectilinear coordinates

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

$$R = \frac{(L_{SN})_P}{\sqrt{(L_{SS})_P (L_{NN})_P}} \tag{17}$$

$$(L_{SN})_P = \sum_{i=1}^{m} (\overline{X}_{Pi})(lg S_i) - \frac{1}{m}\left(\sum_{i=1}^{m} \overline{X}_{Pi}\right)\left(\sum_{i=1}^{m} lg S_i\right) \tag{18}$$

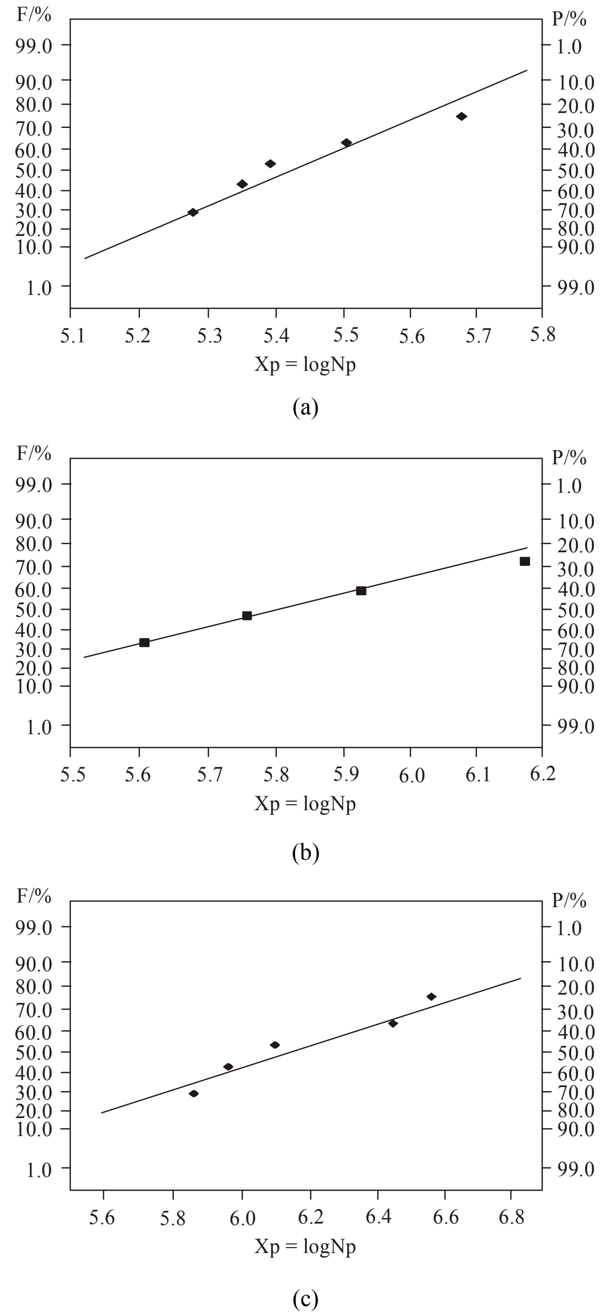

Fig. 4: Test of distribution type for fatigue life of submarine pipelines, (a) stress level A, (b) stress level B, (c) stress level C

$$(L_{NN})_P = \sum_{i=1}^{m} (\overline{X}_{Pi})^2 - \frac{1}{m}\left(\sum_{i=1}^{m} \overline{X}_{Pi}\right)^2 \tag{19}$$

$$(L_{SS})_P = \sum_{i=1}^{m} (\lg S_i)^2 - \frac{1}{m}\left(\sum_{i=1}^{m} \lg S_i\right)^2 \tag{20}$$

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.

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