Fatigue Life Calculation of Tubing for In Situ Drilling Rig

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Abstract. The severe bending strain that the tubing of the in-situ drilling rig is subjected to during the operation under pressure, which exceeds the elastic limit, will cause periodic plastic deformation of the tubing of the in-situ drilling rig, so that fatigue cracks will occur on the internal and external surfaces of the tubing of the in-situ drilling rig and expand rapidly, leading to the greatly shortened service life of the tubing of the in-situ drilling rig. Based on the stress analysis of the dangerous points of the tubing of the in-situ drilling rig, the relationship between the predicted and the standard measured tubing life of the in-situ drilling rig is obtained in this paper. The number of tubing cycles of in-situ drilling rig decreases sharply with the increase of internal pressure. The greater the internal pressure is, the greater the circumferential stress and uniaxial alternating stress are, which causes the number of tubing cycles of in-situ drilling rig to decrease when tubing fails. It shows that the fatigue life of tubing of in-situ drilling rig is significantly affected by internal pressure.

Keywords: drill in situ, tubing, fatigue life, internal pressure.

1. Introduction

According to statistics, about 50% - 90% of the failures of metal material structures of modern construction machinery are caused by fatigue damage. Especially in recent years, with the development of machinery towards high temperature, high speed and large size, the stress of machinery is getting higher and higher, the service conditions are getting worse and worse, and fatigue damage accidents are emerging in endlessly. Therefore, a large amount of human and material resources have been invested or are being invested to carry out research in this field at home and abroad. The first person who systematically studied the fatigue phenomenon was the German engineer Wholer. In 1871, he put forward the concepts of S-N curve and fatigue limit, which laid the foundation for metal fatigue and was known as the "father of fatigue". In 1920, Griffiht created fracture mechanics, known as the "father of fracture mechanics". In 1945, American Miner formulated the linear cumulative damage theory proposed by Palmgren in 1924 on the basis of a large number of experimental studies on the problem of fatigue cumulative damage, and formed the Palmgren Miner linear cumulative damage rule, which is still in use today. In 1961, Neuber began to study fatigue life with local stress and strain, and proposed Neuber's rule. On the basis of Manson Coffin's research[1], Wetzel put forward a method for estimating fatigue life based on stress and strain analysis - local stress and strain method in 1971. Based on the study of uniaxial low cycle fatigue, the study of multiaxial low cycle fatigue has been widely carried out[2]. For the low cycle fatigue problem under multiaxial stress, there is a large error between the results obtained by applying the above theory and the test values. For example, Libertiny research believes that the von mise Scriterion does not consider the influence of hydrostatic pressure. Garud Brown and Mi11er[3] respectively reviewed the research on multiaxial fatigue, and believed that although many multiaxial low cycle fatigue failure criteria have been proposed, a universally applicable criterion has not been found. In a word, there are three main methods for damage accumulation and life estimation of multiaxial low cycle fatigue failure: equivalent strain method, energy method and critical surface method.

The research on the low cycle fatigue of the in situ drilling tubing mainly refers to the prediction method of coiled tubing[4]. Based on the experimental results, TiptnoNweman and Newburn analyzed a large number of failure theories currently used to study multiaxial low cycle fatigue, and established a life estimation model based on Miner's linear accumulation theory of fatigue damage. The results showed that the estimation results were relatively ideal when the internal pressure was small[5].

However, with the further increase of the internal pressure of coiled tubing, it was difficult to explain the damage mechanism caused by circumferential stress with the linear accumulation damage theory. In order to estimate the low cycle fatigue life of coiled tubing under multiaxial stress, Collin S proposed the concepts of equivalent stress and equivalent total strain amplitude[6]. The equivalent total strain amplitude is a function of multiaxial elastic-plastic stress state, and the life can be estimated according to the low cycle fatigue S-N curve obtained under the equal effect amplitude and uniaxial stress state; By using the modified Goodman equation or empirical formula based on specific material data, the equivalent uniaxial average stress cycles can be converted into equivalent fully retarded cycles. Wu[7] estimated the working life of coiled tubing by comprehensively analyzing various influencing factors and using empirical coefficient method. For the actual working life of coiled tubing, some empirical coefficients must be multiplied on the basis of the theoretical estimated life[8]. These empirical coefficients mainly include: working corrosion coefficient, yield strength compensation coefficient of coiled tubing, reliability coefficient of life estimation, and stress concentration coefficient. Although this method is more suitable for practical engineering applications, there are too many empirical coefficients, so there is still a large error between the predicted life and the actual life.

2. Stress analysis of dangerous points of tubing of in-situ drilling riG

2.1. Bending tensile stress

During the operation of the tubing of in-situ drilling rig, bending stress and expansion stress will be generated due to the effect of circulating bending and internal liquid pressure. Since the stress generated by the internal fluid pressure of the tubing of the in-situ drilling rig is basically the same along the circumference of the tubing of the in-situ drilling rig[9], and the bending stress varies with the distance from the neutral axis, the most dangerous point of the tubing of the in-situ drilling rig must be on the internal and external surfaces of the tubing of the in-situ drilling rig far from the neutral axis. Mechanical analysis shows that the outer surface point of the in-situ drilling tubing farthest from the bending support point is the most dangerous point. The bending tensile stress of the in-situ drilling tubing caused by bending on the drum and guide arch at this point is:

$$\sigma_{ar} = \frac{d_o E}{D_r + d_o}$$

$$\sigma_{ag} = \frac{d_o E}{2R_g + d_o}$$

Where: σ_{ar} —Bending tensile stress caused by bending of an in-situ drill tubing on the drum, MPa;

σ_{ag} —Bending tensile stress caused by the bending of the oil pipe of the in-situ drilling rig on the guide arch, MPa;

d_o —Outer diameter of oil pipe of in-situ drilling rig, mm;
E —Elastic modulus, MPa;
D —Drum diameter, mm;
R —Radius of guide arch, mm.

2.2. Radial stress and circumferential stress

The radial stress caused by internal pressure is 0, and the circumferential stress is:

$$\sigma_\theta = \frac{2d_i^2 p_i}{d_o^2 - d_i^2}$$

Where: σ_θ—Circumferential stress,MPa;

d_i—Inside diameter of oil pipe of in-situ drilling rig, mm;

p_i—Internal pressure of oil pipe of in-situ drilling rig, MPa;

d_o—Same as above.

2.3. Equivalent stress

According to foreign research results and foreign experimental data on the tubing of in-situ drilling rigs, it is found that when the material and specification of the tubing of in-situ drilling rigs are certain, the low cycle fatigue life is most significantly affected by the internal pressure, followed by the bending stress. For an in situ drilling tubing, the drum diameter and the bending radius of the guide arch are generally fixed, that is, the bending stress borne by the in situ drilling tubing during operation can be regarded as an invariant[10]. Although the stress state of the in situ drilling tubing will change when the pressure changes, the bending stress can be treated as a constant term in the equivalent stress formula. Since the stress at the dangerous point is only related to bending stress and circumferential stress caused by internal pressure, and the bending during the operation of the tubing of the in-situ drilling rig is generally plastic bending, the equivalent stress formula of the tubing of the in-situ drilling rig can be defined as follows:

The equivalent stress formula of the in-situ drill tubing bent on the reel can be expressed as:

$$\sigma_r = \sigma_{ar} + a\sigma_\theta^\beta$$

Where: σ_r—Equivalent stress of in-situ drill tubing bent on the drum, Mpa;

σ_{ar}, σ_θ—The meaning is the same as above;

α, β—The weight coefficient and index determined by experiments are generally taken as: α =2.46, β =1.61.

The equivalent stress formula of the in-situ drilling tubing bent on the guide arch be expressed as:

$$\sigma_g = \sigma_{ag} + a\sigma_\theta^\beta$$

Where: σ_g—Equivalent stress of in-situ drill tubing bent on the guide arch, MPa;

σ_{ag}, σ_θ, α, β—The meaning is the same as above.

3. Fatigue life prediction model for tubing of in-situ drilling rig

Assume that the total cycle life of the tubing of the in-situ drilling rig under the independent action of the equivalent stress level on the drum is; The total cycle life under the independent action of equivalent stress level on the guide arch is. According to the fatigue strength theory, there are the following relationships:

$$N_1 \bullet {\sigma_r}^2 = N_2 \bullet {\sigma_g}^2 = N_M \bullet \sigma_M^2$$

Where: N_M—Median life of tubing for in-situ drilling;

σ_M—The stress corresponding to the median life of the tubing of the in-situ drilling rig.

After the oil pipe of the in-situ drilling rig passes through the reel and the guide arch once, the oil pipe of the in-situ drilling rig will be subjected to one σ_r action and two σ_g actions, and the resulting damage is obtained according to Miner's linear cumulative damage theory:

$$1/N_1 + 2/N_2$$

If the oil pipe of the in-situ drilling rig is fatigue failure after N strokes under the joint action of σ_r and σ_g, according to the linear cumulative damage theory, the total damage at failure is one, then:

$$N(1/N_1+2/N_2)=1$$

Namely:

$$1/N_1+2/N_2=1/N$$

The service life of the oil pipe of the in-situ drilling rig can be obtained from the formula (6) and the following formula:

$$N=\frac{N_M\bullet\sigma_M^2}{\sigma_r^2+2\sigma_g^2}$$

The predicted life after material conversion is N^*:

$$N^*=\frac{N_M\bullet\sigma_M^2}{\sigma_r^2+2\sigma_g^2}\left(\frac{\sigma_{wi}}{\sigma_{wb}}\right)^2$$

Where: σ_{wi}—Final tensile strength of the reference material;

σ_{wb}—Final tensile strength of other materials;

The meaning of other symbols is the same as above.

It can be seen from equation (11) that the required fatigue life must be obtained $N_M\bullet\sigma_M^2$ and $\left(\frac{\sigma_{wi}}{\sigma_{wb}}\right)^2$.

$$N_M\bullet\sigma_M^2=\left(\frac{E}{2}\ln\frac{100}{100-\varphi}\right)^2$$

$$\left(\frac{\sigma_{wi}}{\sigma_{wb}}\right)^2=\left[\frac{\ln\frac{100}{100-\varphi_i}}{\ln\frac{100}{100-\varphi_b}}\right]^2$$

In the above two formulas:

φ—The reduction of area is obtained from the experiment. For the tubing material of QT-700 in-situ drilling rig, the experiment shows that the reduction of area is 53%;

φ_i—Reduction of area of material with tensile strength of σ_{wi};

φ_b—Reduction of area of material with tensile strength of σ_{wb}, reduction of area of reference material Rate.

Note: When calculating the fatigue life of the oil pipe of the in-situ drilling rig with Equation (4-11), if only one material is calculated (without comparing the tensile strength), $\frac{\sigma_{wi}}{\sigma_{wb}}=1$,even $\left(\frac{\sigma_{wi}}{\sigma_{wb}}\right)^2=1$.

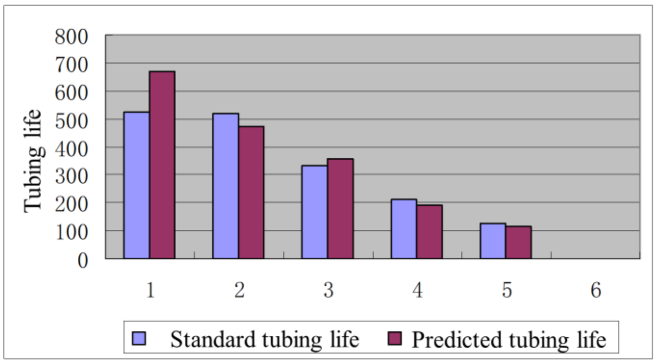
4. Analysis and discussion

According to this model, the fatigue life of tubing in in-situ drilling rig is predicted. Some fatigue test data of in-situ drilling tubing obtained by Newman K. R and Brown P.A et al. were used for verification. The data were obtained on the standard fatigue test device for in-situ drilling tubing developed by Schlumberger Downell Company in 1993. See Table 1 and Figure 1 for comparison.

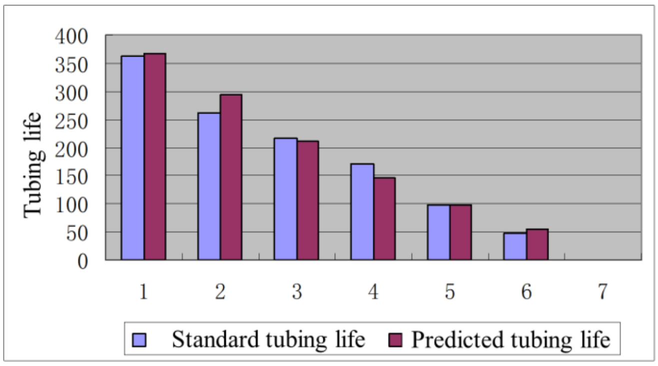
The data in the fifth column in Table 1 are real scale experimental data; The data in the sixth column are obtained by using the standard fatigue test device for tubing of in-situ drilling rig; The data calculated by the life prediction model established by the data in the seventh column.

Table 1. Model verification and result comparison

tube diameter D/mm	wall thickness t/mm	Bending radius R/mm	Internal pressure p/MPa	Full scale test cycles Nr/time	Number of test cycles of standard testing machine Ns/times	Number of predicted cycles Np/time	Error/%
φ31.75	2.210	1 219	1.72	597	522	669	-12.00*
φ31.75	2.210	1 219	10.34	525	517	474	9.70*
φ31.75	2.210	1 219	20.68	423	333	355	16.00*
φ31.75	2.210	1 219	27.58	--	212	190	10.30
φ31.75	2.210	1 219	34.48	123	128	117	4.87*
φ44.45	2.769	1 219	1.72	--	362	367	4.40
φ44.45	2.769	1 219	6.89	--	262	295	12.50
φ44.45	2.769	1 219	13.79	--	216	212	1.85
φ44.45	2.769	1 219	20.68	--	170	146	14.10
φ44.45	2.769	1 219	27.58	--	99	99	-0.73
φ44.45	2.769	1 219	34.48	--	49	55	-12.20
φ44.45	3.962	1 219	13.79	--	311	342	-9.90
φ44.45	3.962	1 219	27.58	--	235	219	6.81



(a) The diameter of oil pipe is 31.75mm



(b) The diameter of oil pipe is 44.45mm

Figure 1. Relationship between predicted and standard measured tubing life of in-situ drilling rig

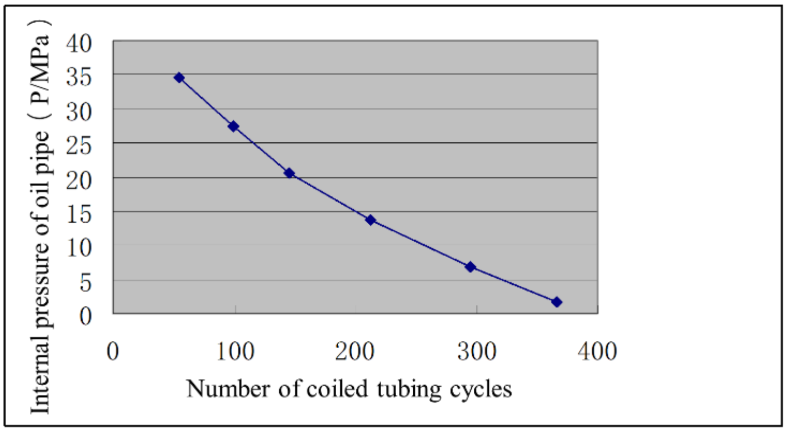


Figure 2. Pressure Life Prediction Curve of Tubing of in situ Drilling Rig

From the above chart results, it can be seen that the calculated life value of the life prediction model established in this paper is basically close to the experimental value. It shows that this model is basically correct. However, there are still some data errors, on the one hand, because there are few fatigue test data of in-situ drill tubing, and the dispersion of test data is large; On the other hand, because there are many factors that affect the fatigue life of the tubing of the in-situ drilling rig, the error of the experiment itself may be large.

Based on the above experimental data, the curve for predicting the relationship between the internal pressure and fatigue life of the tubing of the in-situ drilling rig is drawn as shown in Figure 2. The number of tubing cycles of in-situ drilling rig decreases sharply with the increase of internal pressure. The greater the internal pressure is, the greater the circumferential stress and uniaxial alternating stress are, which causes the number of tubing cycles of in-situ drilling rig to decrease when tubing fails. It shows that the fatigue life of the tubing of the in-situ drilling rig is significantly affected by the internal pressure. Therefore, the internal pressure of the tubing of the in-situ drilling rig should be controlled as much as possible during the actual use.

5. Conclusion

1) The complex stress is transformed into the equivalent uniaxial tensile stress by using the equivalent stress of the tubing of the in-situ drilling rig, that is, the multiaxial low cycle fatigue problem is simplified into the uniaxial low cycle fatigue problem;

2) On the basis of previous research results, through theoretical research, the strain life relationship of low cycle fatigue of in-situ drill tubing is transformed into stress life relationship, and the life problem of different materials is transformed into the life problem of the same material by using the fatigue cumulative damage theory and transformation;

3) The life prediction model of tubing for in-situ drilling is established, and the semi empirical formula for predicting the working life of tubing for in-situ drilling is obtained, which is basically correct through experimental verification.

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