The Crack Nucleation Life of the TLP Flexjoint

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Abstract. Since the tension leg platform (TLP) needs to work in the ocean for a long time, it requires a high cost to replace any components. The working life is a key design element. The flexjoint is the crucial load-bearing component in the TLP mooring system. It has a multilayer metal/elastomer structure, and its working life generally depends on the rubber portion. In this paper, the fatigue life of flexjoint is calculated by crack nucleation method. Firstly, the dumbbell test piece is used to perform the uniaxial tensile fatigue test. The strain-fatigue life curve of the rubber material is obtained. The fatigue life of the flexjoint is calculated by the crack nucleation method. The fatigue test device of the flexjoint is developed, and the calculation result of crack nucleation life is verified by experiments.

1. Introduction

The tension leg platform is a deepwater production platform, which is mainly composed of a topside, a hull, and tendons and so on. The tendons are used for connecting TLP and the sea bottom. In order to meet the unique requirements of deepwater connection, a specific tendon connector is designed to complete the connection among the tendon, TLP and underwater pile foundation. In order to reduce the local bending stresses caused by vessel motions and environmental forces, a flexjoint is designed in each of the tendon connectors [1, 2]. It provides a certain rotational flexibility for the tendon connector, reduces the stress concentration at the end of the tendon, and also withstands a large axial pull. The flexjoint is manufactured by Laminated Elastomeric Component (LEC). LEC is a multilayer metal/elastomer structure in which the rubber is bonded to the metal. Compared to rubber materials, LECs can withstand higher compressive loads and increase compression stiffness while maintaining a relatively low shear stiffness. Based on the above advantages, LECs are used in many engineering equipments, such as the rubber bearing between the bridge and the pier, which can absorb the lateral vibration of the bridge [3]. A Leg Mating Unit (LMU) for offshore platform installation acts as a buffer during platform installation [4]. A solid booster flexible bearing joint in the solid rocket motor (SRM) allows the nozzle to deform in any given direction under engine control [5]. Spherical elastomeric bearings used in helicopter motors can withstand centrifugal and lateral forces to accommodate rotation, flip and leading lag movement [6]. Since TLP will work underwater for a long time and replacing any component requires a high cost, the design life becomes a key design element. The flexjoint is the crucial bearing component in TLP, so its fatigue performance is very significant. In practical work, the stress in the metal layer of flexjoint is small, so it’s working life generally depends on the rubber part.
In general, rubber fatigue failure is mainly divided into two stages. In the first stage, the microscopic defects inside the rubber are gradually converted into visible cracks, i.e., crack nucleation. In the second stage, the cracks slowly expand and eventually cause fatigue damage. According to this characteristic, two different methods are developed to calculate rubber fatigue life, i.e., crack nucleation method and crack propagation method [7].

The crack nucleation method was first proposed by Wöhler [8] to calculate the fatigue life of the train axle. This method was then applied to rubber material by Cadwell et al [9]. The method considers that the fatigue life of rubber can be determined by the stress-strain data at each point on the test piece. This method often predicts the fatigue failure of rubber by strain, stress or energy. Since it can be obtained directly from the displacement data, strain is the most commonly used rubber fatigue prediction parameter. Suryatal et al. [10] used the maximum principal strain to predict the fatigue life of the compressed neoprene elastic pad. They found that increasing the maximum compressive load caused the maximum principal strain to rise, which in turn reduced the fatigue life. Li et al. [11] used the Mooney-Rivlin model to perform FE simulation on rubber specimens and used the maximum principal strain as the fatigue prediction parameter. The test results can be accurately fitted. Kim et al. [12] and Woo et al. [13] used Green Lagrangian strain as the fatigue prediction parameter of natural rubber dumbbell specimens. By comparing with the strain energy density, it was found that the Green Lagrangian strain would better fit test results. In this paper, the fatigue life of a flexjoint was calculated using the crack nucleation method. Firstly, the uniaxial tensile fatigue test was carried out using the dumbbell test piece, and the strain-fatigue life curve of the rubber material was obtained. The crack nucleation life of the flexjoint was calculated. A flexjoint fatigue test device was developed, and the calculation result was verified.

2. Rubber Crack Nucleation Life Calculation Method
Generally, due to processing defects or stress concentration, the rubber material has tiny defects inside. After under a long-term alternating loading, the micro-defects expand and eventually lead to crack nucleation. The fatigue life of a flexjoint calculated by the crack nucleation method is essentially the number of loading cycles required to produce an initial crack in the flexjoint. In mechanical design or fatigue analysis, the number of cycles of which a microscopic defect extends to a macrocrack of 1 mm length is defined as the crack nucleation lifetime. In order to calculate the crack nucleation life, two methods are generally used. One method uses nominal stress, and the other one uses strain. Since the rubber material is subjected to large deformation, the strain can be relatively more convenient to measure with displacement. Therefore, the nucleation life of the flexjoint is studied using the strain-fatigue life curve and equation. The strain-fatigue life curve of rubber is one of the intrinsic properties of rubber materials, which needs to be obtained through experiments.

The maximum principal strain is used as the fatigue life parameter here, because the initial crack of the rubber generally appears in a direction perpendicular to the maximum principal strain. The maximum principal strain in the flexjoint can be calculated by the FE method.

3. Rubber Uniaxial Tensile Fatigue Test
In order to obtain the strain-fatigue life curve, it is necessary to perform a uniaxial tensile fatigue test on the rubber. At present, the two most commonly used test pieces for this test are sheet-shaped dumbbell test pieces and column-shaped dumbbell test pieces, as shown in figure 1. The advantage of the cylindrical dumbbell test piece is that the uniaxial tension and uniaxial compression fatigue test can be performed simultaneously, and the fatigue life of the rubber material can be accurately predicted when the fatigue property of the rubber material is studied using the maximum principal strain. The advantage of the sheet-shaped dumbbell test piece is that it is easy to process. One only need to cut the rubber piece by the cutter. The test period for achieving fatigue life is shorter, and the fatigue life error predicted by using the test piece is not more than 28%, in engineering application. It can be used to replace the column dumbbell test piece.
Taking into account the processing cost and test cost, the sheet-shaped dumbbell test piece is selected to get the \( \varepsilon-N \) curve of the rubber material. The nitrile rubber is used, and the dumbbell test piece is provided by Tieling Yingang Rubber Factory. The total length of the test piece is 100 mm, the length of the stretched part is 20 mm, the width is 5 mm, and the thickness is 2 mm, as shown in Figure 2 (a). The test piece was designed to break quickly once a 1 mm length crack generated, so only the number of load cycles \( N_f \) at when the test piece broke was recorded.

The test was carried out at room temperature and a sinusoidal displacement fatigue load of 2 Hz was applied to the test piece using a Zwick 8801 tensile fatigue test rig, as shown in Figure 2(b). In this test, three different loading conditions were proposed. The minimum displacement was 0 and the maximum displacements were 15 mm, 20 mm and 25 mm, respectively. The corresponding maximum nominal strain \( \varepsilon \) was 0.56, 0.69 and 0.81. Three same dumbbell test pieces were used for each set of loading to eliminate individual differences.

Figure 3 shows the \( \varepsilon-N \) curve obtained in experiment, whose horizontal and vertical coordinates are in a logarithmic coordinate system. According to the relationship between damage parameters and life, the \( \varepsilon-N \) equation is obtained by curve fitting as

\[
N_f = 2.907 \times 10^5 \varepsilon_L^{-3.245}
\]  

(1)
4. Nucleation Life of Flexjoint

It is assumed that the failure of the flexjoint does not occur in the metal portion. According to the above, the crack nucleation life of the rubber material under corresponding loading condition has been obtained by experiments. At this time, the FE method is needed to calculate the maximum principal strain of the rubber part in the flexjoint. In this section, the nitrile rubber flexjoint with three layers of metal plates, as shown in figure 4, was used. The crack nucleation life of the sample subjected to compression and rotational loads at the same time was calculated.

![Figure 3. ε-N curve of NBR.](image)

![Figure 4. Flexjoint prototype.](image)

Firstly, the FE method is used to simulate the whole flexjoint, and the 1/2 three-dimensional FE model of the rubber layer is established. The rubber was simulated using the Yeoh constitutive model. The parameters of the nitrile rubber material, as shown in table 1, was obtained by fitting the data of uniaxial tensile, simple shearing, biaxial tensile and volume compression test. A reference point RP-1 is established at the origin of the flexjoint. The top of the rubber layer is fixed, and the bottom is coupled to RP-1. In actual work, the rotational load of flexjoint comes from the horizontal movement of the tension leg platform, and the vertical compression load comes from the heave motion of the tension leg platform, which are both the displacement-controlled. Therefore, two analysis steps are set. In the analysis step-1, an angular displacement of 5° in the counterclockwise direction around the z-axis is applied to the RP-1. The displacement of 1.5 mm in the y direction is applied to the RP-1 and the deflection angle is kept constant in the analysis step-2. Figure 5 shows the maximum principal strain cloud diagram of the flexjoint. It can be seen that the maximum principal strain occurs in the first rubber layer of the flexjoint, and the maximum engineering principal strain value at the critical position is 1.894. The value is brought to the Eq.1, and the crack nucleation lifetime is obtained to be 37,000 times.
Table 1. Constitutive model parameters of NBR.

| Yeoh | $C_{10}$ [MPa] | $C_{20}$ [MPa] | $C_{30}$ [MPa] | $D_1$ [MPa$^{-1}$] | $D_2$ [MPa$^{-1}$] | $D_3$ [MPa$^{-1}$] |
|------|----------------|----------------|----------------|---------------------|---------------------|---------------------|
| Parameters | 0.307 | -0.0109 | 0.000476 | 0.00168 | 1.29e-5 | -1.45e-7 |

Figure 5. Maximum nominal principal strain of flexjoint under 0.5° angle and 100 kN compression.

5. Fatigue Test of Flexjoint

According to the foregoing description, the flexjoint is mainly subjected to a compressive load and a rotational load during operation. The rotational load comes from the swaying motion of TLP, and the compression displacement comes from the heave motion caused by the sway motion. Based on the same loading principle, this paper designs a flexjoint fatigue tester, as shown in figure 6. A hydraulic cylinder horizontally pushes the bottom of the swinging shaft, and the flexjoint will rotate by the swinging shaft. At the same time, the swinging shaft moves downward to compress the flexjoint. Since the fatigue tester needs to provide horizontal tension and thrust with opposite magnitudes in the same direction, and the load is large. By considering the control difficulty and construction cost, it is finally decided to use a hydraulic cylinder to provide loading. A solenoid valve is used to control the direction of the load. The limit switch is used to control the maximum horizontal displacement, and record the number of changes of the limit switch signal, which is recorded as the number of load cycles.

Figure 6. Fatigue tester of flexjoint.

The flexjoint fatigue test was carried out at room temperature, and the nitrile rubber flexjoint sample was the same one described in the previous section. According to the above description, the flexjoint load is displacement control with a rotational load of ±5° and a compressive load of 0 mm to 1.6 mm. Considering the transmission capacity of the hydraulic system, the load frequency was set to 0.5 Hz. When a significant crack appears on the flexjoint, the number of loadings at this time is the crack nucleation life. The nucleation fatigue life of the flexjoint obtained by the experiment is about 28,000
times, and the error with the theoretical calculation result is 32%, which is considered to meet the engineering requirements.

6. Summary
In this paper, the fatigue life calculation method of flexjoint is studied. The nucleation life of the flexjoint was calculated to be 37,000 times with the maximum engineering principal strain as the fatigue parameter. A flexjoint fatigue test device was developed. The nucleation fatigue life of the flexjoint crack obtained by the test was about 28,000 times, and the error with the theoretical calculation result was 32%, which was considered to meet the engineering requirements.

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