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Fatigue life prediction of wire rope based on stress field intensity method

Dan Zhao*, Shaogang Liu, Qingtao Xu, Feng Shi, Wenyi Sun, Liqin Chai

College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin City, Heilongjiang Province 150001, China

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ABSTRACT

In the paper, on the basis of the stress field intensity method, the internal complex wingding structure of 6 × 31SW + FC type wire rope is analyzed and calculated. As a first step, considering the weakening speed of weight function in the stress field intensity method is too fast, a modification is presented to make it more suitable for the calculation of the fatigue life of wire rope. The load spectrum of the critical locations of wire rope is then established, based on the Costello mechanical model and the actual working conditions. Through the stress field intensity method, the time history curve of stress field is then obtained. Subsequently, the fatigue life of wire rope is calculated by using the linear cumulative damage theory of fatigue. The wire rope fatigue test rig is established, and the experimental value of the fatigue life of wire rope is compared with the theoretical calculation value. The results show that the experimental load of 90 t is the demarcation point of high and low cycle fatigue of wire rope, the theoretical values and the test results are close to each other in the fatigue cycle, which proves the effectiveness of the stress field intensity method in predicting the fatigue life of the wire rope.

1. Introduction

The wire rope has functions of lifting, pulling, tightening and carrying in the process of material handling. It has been widely used in cranes, aviation equipment parts traction, ship fixed cable and other occasions [1–2] due to its benefits including high strength, light weight, smooth working and Strong ability to bear dynamic load. It can be seen that the wire rope has become an important component in the field of engineering. However, it is prone to fatigue, wear and even fracture during use, which leads to engineering accidents. Therefore, it is necessary to use a reasonable calculation method to predict its fatigue life.

Several studies in the life prediction method of wire rope have been recently conducted such as Kumar and Botsis [3] obtained the analytical expression at the time of maximum contact pressure by using linear deformation derivative of the multilayered strands under the action of tension and torsion, respectively. And the effect of a series of connection parameters and material performance on the contact stress is further studied. Giglio and Manes [4] evaluated the internal and external stress state of single-strand wire rope using analytical formulas. Zhang et al. [5] tested the fatigue life of the wire rope and found that it is inversely proportional to the depth of wear.

The proposed studies are all aimed at predicting the high cycle fatigue life of wire rope. In the process of mine hoisting, the breakage of wire rope occurred frequently due to the overload of wire rope during the strength degradation. Therefore, the low cycle fatigue life of the wire rope also needs to be analyzed. Dagang Wang [6] studied the effect of end-of-line mass on fatigue parameters during a working cycle. Dagang Wang [7,8] measured the effect of displacement amplitude on the life of wire rope under low cycle

* Corresponding author.
E-mail addresses: zhaodan@hrbeu.edu.cn (D. Zhao), liushaogang@hrbeu.edu.cn (S. Liu), chailiqin@hrbeu.edu.cn (L. Chai).

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fatigue by fatigue test rig. A. Cruzado et al. [9] studied the low-cycle fatigue behavior of wire rope using a multi-axis fatigue SWT critical plane.

There are various prediction methods for fatigue life. A. Cruzado et al. [9] studied the effect of wear on the life of fine steel wire and introduced four methods of fatigue life prediction: Manson universal slope method, Muralidharan modified universal slope method, median method and fatigue S-N curve method, and they pointed out that the Manson method and the median method results were closer to the experimental results, and the modified universal slope method was relatively conservative in predicting the fatigue parameters, and the calculation of the fatigue life in the low cycle was more accurate. Zhang Chengcheng [10] proposed stress severity factor method for the fatigue of aircraft fasteners. Guo Jiansheng [11] estimated the fatigue life of welded steel structure using fracture mechanics, which can be used for the prediction of crack propagation life with crack structure. Shang Deguang [12] proposed a local stress-strain field method that can be used for random cyclic loading. Xiong Weigong [13,14] estimated the wire rope life by using the nominal stress method and the local stress strain method, respectively. The nominal stress method is mainly used to calculate fatigue life dominated by elastic deformation due to it is based on stress fatigue calculation. The local stress - strain method is a kind of fatigue life estimation method on the basis of the research of notch strain and low cycle fatigue, so it is more accurate when the calculation of the fatigue life applied in the low cycle.

Based on the above working conditions and requirements, the stress field intensity method is a method proposed in the process of studying the fatigue damage mechanism, applied for multi-axis fatigue life evaluation under complex load, and it is suitable for high and low cycle fatigue calculation [15,16], and the accuracy of the prediction is relatively high. It has been widely used in the life prediction of structures such as aviation structure and flange welding parts. Zhou Shangmeng et al. [17] established the model of steel bridge component to tackle the problem using the stress field intensity method, and evaluated the fatigue strength of Biaxial or multi-axis for some special structural details in the bridge structures. Based on the failure mechanism of fatigue damage, Chen Jian [18] studied the principle and the concrete realization process of the stress field intensity method to predict the fatigue life of components, and the significance of each field strength parameter in field intensity method is discussed emphatically. The method presented a parameter–field intensity which reflects the severity of the local damage zone and was used to evaluate the fatigue damage of component [19]. The paper applies the stress field intensity method to the fatigue damage process of the wire rope under complex loading, and the high-low cycle fatigue life of wire rope is predicted by the Miner linear fatigue damage accumulation criterion [20]. The fatigue test rig is established to verify the effectiveness of the stress field intensity method to predict the fatigue life of the wire rope.

2. The basic theory of stress field intensity method

2.1. Stress field intensity method

The definition of stress field intensity method [21] is:

$$\sigma_{FI} = \frac{1}{V}\int_{\Omega} f(\sigma_{ij})\phi(r)dv \tag{1}$$

where σ_{FI} is the filed intensity of notched, Ω notch failure area, the size of the notched area, $f(\sigma_{ij})$ is the failure stress function, $\phi(r)$ is the weight function. For the plane problem, Eq. (1) can be written as

$$\sigma_{FI} = \frac{1}{S}\int_{D} f(\sigma_{ij})\phi(r)ds \tag{2}$$

The S in the formula is the area of the notch failure area D.

Where Ω is usually the size of multiple grains, and it is usually a random variable because of the effects of many variables, such as material performance, notch parameters. At present, the shape of many fatigue failure zones need to be determined by experiments. The stress of wire rope obtained at the time of calculation is smaller than its yield stress, therefore, the paper cited the calculation method of the literature [22], and then take $r = 3.55$ mm after it is calculated.

The failure stress function $f(\sigma_{ij})$ reflects the influence of stress field and material properties on the notched strength, and it is related to the failure mechanism of the material. The application of the strength theory will vary for different materials. Now most of the engineering structural materials are isotropic metal materials, the $f(\sigma_{ij})$ can be obtained by the equivalent stress formula of Von Mises.

$$f(\sigma_{ij}) = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}} \tag{3}$$

The weight function $\phi(r)$ represents the contribution of the stress at the point Q to the peak stress of the $|r|$ in physics. The effect of surface on fatigue damage is relatively large, while the internal is small. Generally speaking, the stress concentration at the root of the notch is the most severe. So there exists:

① $0 \le \phi(r) \le 1$, and $\phi(r)$ is a generalized monotone decreasing function of $|r|$;

② $\phi(r) \equiv 1$, The maximum stress of the notch root at this moment has the greatest effect on the fatigue damage;

③ When the stress gradient $G = 0$, $\phi(r) \equiv 1$, under this condition, smooth specimen or full yield specimen has the same effect on fatigue damage throughout the failure zone.

For smooth specimens, $K_T = 1$, so $\phi(r) = 1$; the stress can be considered equal everywhere in the smooth specimen, so the failure