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Study of component structural equivalent fatigue based on a combined stress gradient approach and the theory of critical distance

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ABSTRACT

Fatigue limit load is one of the most important factors and concerns in designing and manufacturing critical mechanical parts such as crankshafts. Traditionally, this governing parameter is obtained via a time and money-consuming experiment and analysis of a simple structure while it becomes theoretically complicated for sophisticated cases. In this paper, proper extrapolation methods to calculate the stress gradient in the stress concentration area are first chosen to obtain the material parameter using the theory of critical distance (TCD) indirectly. Then the fatigue limit load of crankshafts with the same material properties but different structures are computed. Validation between the prediction and the experimental results shows that this combined approach may provide a more satisfactory result in terms of fatigue limit for quick engineering prediction.

1. Introduction

Long working life is required for critical engineering parts such as a crankshaft (where the longevity of the fatigue limit is about 10^7 cycles), transmission shaft and others [1]. Thus, correct prediction of the fatigue limit from the designing phase becomes important. Traditionally, time consuming and cost ineffective methods are adopted in engineering applications via the analysis of experimental data for relatively simple structures. However, it becomes a tough barrier to overcome if the structure has a complicated shape, such as a crankshaft. In addition, residual stress, manufacturing defects and the stress concentration factor that may have a dominant influence over the fatigue strength are theoretically difficult to quantify, leading an unsatisfactory prediction results.

To solve this dilemma, pioneer attempts have been conducted in recent years. Taylor and Tanaka proposed the theory of critical distance to predict the fatigue life of the notched component. This theory considered that the fatigue life of a given component not only depended on the maximum stress (which always occurs on the surface of the component), but was influenced by the stress distribution within the vicinity of a stress concentration point [2–10]. Based on this, Taylor predicted the fatigue life of some simple notched or welded components with good results. Taylor also introduced a crack-modeling technique to predict the fatigue limit load of the crankshaft by creating a straight crack in the infinite plane with the same stress distribution with the component [11–13]. However, prediction results were not effective enough due to the differences in the stress state. Later, Chen Xiao-ping produced a method to predict the fatigue limit load of the crankshaft by using an equivalent notched component and asymptotic interpolation integration method with improved prediction, but the prediction was only applied to crankshafts with similar structures (the same fillet radius) [14].

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On the other hand, the material parameter of the structure also matters in determining the fatigue limit load [15–18]. Spaggiari [19] compared the classical stress gradient method and theory of critical distance (TCD) to predict the fatigue life of an infinite two-dimension component with a V-shape notch. In this way some parameters of the material can be obtained easily with a decent accuracy, especially for a complicated shaped structure. Also, other methods are proposed to deal with the material parameter determination problem such as the implicit gradient approach [20–21], but the applicability of these methods in complicated shaped engineering structures such as a crankshaft has not been studied yet.

Therefore, this paper proposes a new method by taking advantage of a combination of two methods, i.e. stress gradient approach and the theory of critical distance to jointly predict the fatigue limit load for the geometrically complicated crankshaft. Firstly, the stress gradient of the crankshaft under its limit load is computed with the finite element and extrapolation method. Secondly, some critical material parameters are based on TCD and finally the fatigue limit load of a crankshaft made by the same material is predicted and validated via a comparison with the experimental results.

2. Method

The classical stress gradient method was proposed in the 1950s [15–18]. This method believes that the fatigue life of a component is affected not only by the maximum stress, but also by a support factor, so the effective stress which can be calculated by the maximum stress and the support factor (SF) makes a crucial role in the damage process of the component. This method was based on the linear elastic stress analysis, and its first step is to calculate the stress gradient at the stress concentration point by the equation below:

$$G_\sigma = \frac{d(\sigma_x)}{dx}(x=0) \tag{1}$$

In this equation, G_σ is the stress gradient at the stress concentration point, x is the path in which the crack generates and propagates, and σ_x refers to the distributions of the stress along the x path as shown in Fig. 1. The maximum stress occurs at the point $x = 0$.

The second step is to calculate the SF of the component, the SF is defined as:

$$v = 1 + \sqrt{\frac{G_\sigma \rho}{\sigma(0)}}. \tag{2}$$

Here ρ can be treated as a constant which only depends on the material properties, so in the final step, the effective stress can be calculated as:

$$\sigma_{eq} = \frac{\sigma(0)}{v}. \tag{3}$$

σ_{eq} is the key factor in the fatigue damage process of the component. So for the crankshafts made by the same material, they have the same σ_{eq} when they are in limit conditions. In other words, if we know the limitation of the σ_{eq} of the crankshaft, we can predict the fatigue limit load of the crankshaft made by the same material easily. But this method has two difficulties in acting:

1. For most materials, the parameter ρ cannot be obtained directly, or indirectly by an experiment.
2. For most of the crankshafts, its stress distributions under the limit load cannot be fitted by a simple curve directly, so the stress gradient cannot also be calculated directly.

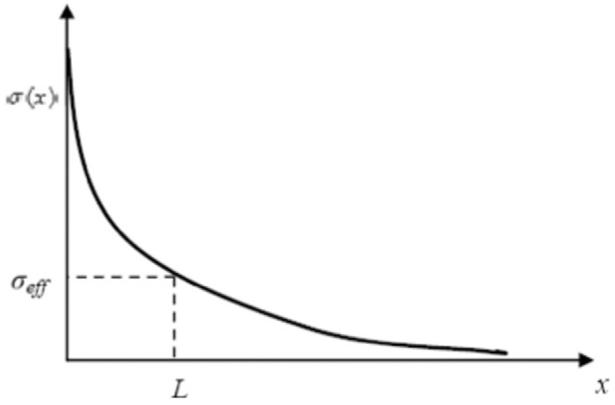

Fig. 1. Stress distribution along the crack propagation path.