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Numerical simulation of steel wheel dynamic cornering fatigue test

Zhan-Guang Zheng*, Teng Sun, Xi-Yong Xu, Shu-Qin Pan, Shuai Yuan

Guangxi Key Laboratory of Manufacturing System and Advanced Manufacturing Technology, College of Mechanical Engineering, Guangxi University, Nanning 530004, PR China

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ABSTRACT

A computational methodology is proposed to simulate wheel dynamic cornering fatigue test and estimate its' multi-axial fatigue life. The technique is based on the critical plane theory and the finite element methods. The prediction of fatigue life is found to be in close agreement with the corresponding experiment. The stress states of wheel are basically biaxial tensile and compression normal stresses during the prototype test. The principal stresses are not proportional and the unstable principle plane is changing with loading direction, which indicates that the fatigue crack may occur first in the circumferential direction of steel wheel.

1. Introduction

Automotive wheel, as a critical component in the vehicle, has to meet the strict requirements of driving safety. Traditionally, the new designed wheel is tested in the laboratory for its life through an accelerated fatigue test before the actual production starts. However, a physical prototype test time lasts at least 7 days and an average design period is 6 months or more depending on the requirement, so the time to test and inspect wheel during development is very consuming. At the same time, because steel wheel is designed for variation in style and has very complex shape, it is difficult to assess fatigue life by using analytical methods. In the last decade, many scholars and wheel manufacturers have been taking increasing attention to numerical analysis of wheel fatigue life [1–6]. Kocabicak and Firat [1] proposes a bi-axial load-notch strain approximation for proportional loading to estimate the fatigue life of a passenger car wheel. Wang and Zhang [2] simulates the dynamic cornering fatigue test of a steel passenger car wheel by the linear transient dynamic finite element analysis and the local strain approach. Li et al. [3] use a through process model to predict the fatigue life of an A356 automotive wheel subject to bending fatigue. Shang et al. [4] simulate the dynamic cornering fatigue tests of a forged magnesium wheel. Firat et al. [5] and Raju et al. [6] simulate of wheel radial fatigue tests based on the local strain approach and the *S*–*N* curve method.

Those researches are very interesting and valuable. For economic reasons, the local strain approach or the *S*–*N* curve method of the uniaxial loading or the bi-axial proportional loading, are used to estimate the fatigue life of an automotive wheel [1–6]. However, for the complex shape of wheel and the dynamic cornering loading, the stress states of wheel may be not the uniaxial or the bi-axial proportional stress, but the more complex multi-axial stress. Therefore, the insight of fatigue failure mechanisms under multi-axial loading conditions is still a practical need in such complex loading conditions [7,8].

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* Corresponding author. Tel./fax: +86 771 3232294.
E-mail address: zhenglight@126.com (Z.-G. Zheng).

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In this paper, a computational methodology based on the critical plane theory and the finite element analysis approach is presented for the fatigue damage assessment of a disk-type automotive steel wheel under cycle cornering loads conditions. The fatigue damage is estimated using the local material responses computed with a bilinear cyclic elasto-plastic model. The fatigue test cycles and the critical crack initiation locations are calculated using effective strain, Brown-Miller damage criterion, rainflow counting method and Palmgren–Miner cumulative damage rule. At last, the computational model predictions are compared with the test results.

2. Fatigue life modeling

A numerical analysis model for fatigue life prediction may be composed of four main computational models. At first, the local stress–strain responses at a structural point under a given cyclic loading history are given. Therefore, a reasonable and efficient material model is required. Under a series of complex loads, a multi-axial damage criterion is used to assess fatigue crack initiation and growth. Cycle counting methods and fatigue damage cumulative model may be given for the evaluation of fatigue life.

2.1. Material constitutive model

Material behavior of wheel is assumed to be in the elasto-plastic state with isotropic hardening and yielded to bilinear isotropic hardening rule. So a bilinear isotropic hardening model is expressed as follows [9]:

$$\sigma = \begin{cases} E\varepsilon & (\varepsilon \leqslant \varepsilon_0) \\ Y_0 + E_T(\varepsilon - \varepsilon_0) & (\varepsilon > \varepsilon_0) \end{cases} \tag{1}$$

where E is elastic module, E_T is work-hardening rate, ε is effective strain, Y_0 is yield limit and ε_0 is elastic strain.

2.2. Multi-axial fatigue damage criterion

Fatigue failure criterion, in which the equivalent stress is a vector, is usually known as the critical plane approach. As shown in Brown–Miller criterion [10], fatigue damage processes are defined with critical material planes, at which a damage parameter attains its maximum for a given loading history. In the critical plane approaches, the fatigue damage events are generally used parametric stress–strain functions involving normal strain and shear strain components. Brown–Miller criterion is expressed as follows [10]:

$$\frac{\Delta\gamma_{\max}}{2} + \frac{\Delta\varepsilon_n}{2} = C_1\frac{\sigma'_f}{E}(2N_f)^b + C_2\varepsilon'_f(2N_f)^c \tag{2}$$

where C_1 and C_2 are material coefficients; $\Delta\gamma_{\max}$ is the shear strain amplitude; $\Delta\varepsilon_n$ is the normal strain amplitude; σ'_f is the fatigue strength coefficient; b is the fatigue strength exponent; ε'_f is the fatigue ductility coefficient; c is the fatigue ductility exponent.

In general, $C_1 = 1.65$, $C_2 = 1.75$, therefore, Eq. (2) can be re-expressed as [10]:

$$\frac{\Delta\gamma_{\max}}{2} + \frac{\Delta\varepsilon_n}{2} = 1.65\frac{\sigma'_f}{E}(2N_f)^b + 1.75\varepsilon'_f(2N_f)^c \tag{3}$$

2.3. Rainflow method of cycle counting

Perhaps the most logically defensible and widely used cycle counting method is rainflow counting method. Wang and Wang [11] has proposed a rainflow counting method based on the critical plane theory. In this method, firstly, shear strain history on the critical plane is counted, and some cyclic periods and retracing points of shear strain are gained. Then, according to the relation of retracing point of shear strain corresponding to the point of normal strain, the maximum amplitude of normal strain in a cycle is calculated. This operation procedure is shown in Fig. 1. There are a shear strain history and a normal strain history in Fig. 1. Based on the rainflow counting method, the shear strain history can be divided into three cycles as 2–3–2′, 6–7–6′ and 1–5–1′. In the range of 2–3–2′, cycle amplitude is $\Delta\gamma_1$ and loading points are 2, 3 and 5. Then, point 2′ in the shear strain history is corresponding to point K in the normal strain history, therefore, the maximum amplitude (ε_{n1}) of normal strain in B–C–D–K can be evaluated. After such a procedure, the first cycle counting result ($\Delta\gamma_1$, ε_{n1}) can be got. Repeat above procedure for the next reversal and continue these steps to the end. The next ($\Delta\gamma_2$, ε_{n2}) and ($\Delta\gamma_3$, ε_{n3}) can also be acquired as shown in Fig. 1 [11].

2.4. Palmgren–Milner linear damage rule

To predict the fatigue life of structures under cyclic loading, generally, there should be a cumulative damage rule. Under the constant amplitude load, the Palmgren–Miner rule (P–M rule) is widely used and commonly accepted.