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Probabilistic Modeling of Damage Accumulation for Fatigue Reliability Analysis

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Abstract

For high-speed trains, reliability prediction of railway axles plays an important role in preventing accidents due to fatigue. Using a nonlinear damage accumulation concept, a probabilistic *S-N* curve and one-to-one probability density function transformation, a probabilistic approach for modeling damage accumulation is developed to analyze the fatigue reliability of railway axle steels. Through characterizing the damage accumulation process as a distribution of degradation path, the proposed method captures a nonlinear damage accumulation phenomenon under variable amplitude loadings. The fatigue reliability is then analyzed and demonstrated through probabilistic modeling of cumulative damage, and an agreement between the predicted results and the experimental measurements under different loading conditions is obtained.

Keywords: fatigue; reliability; probabilistic; damage accumulation; railway axle;

1. Introduction

For railway vehicles, the axles transmit the vehicle weight to the wheels and carry the driving and braking forces under complex loadings [1-3]. Materials ageing, mainly through fatigue damage accumulation, are one of the major factors for a reduction of reliability of railway axles, which often results in derailments, deaths and injuries. As the usage life progresses, fatigue damage in axles accumulates progressively until a damage threshold is reached where failure occurs. Modeling of fatigue damage has received increased attention in recent years [4-6]. Existing models focus on the deterministic fatigue concept, however, the process of fatigue damage accumulation in railway axles is

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stochastic in nature, which results from inherent variability in fatigue resistance of materials as well as the scatter due to service loads in the axles. Accurate life prediction and reliability assessment is a challenging issue in structural integrity assessment of these critical components [7-11].

From the viewpoint of fatigue design, quantification on the relation of fatigue life to the applied stress is critical in reliability-based design of railway axles. In order to estimate fatigue damage under variable amplitude loadings (VAL), a commonly-used method is to calculate an equivalent stress range based on linear damage rule and S-N curve. However, it lacks of assessments on variability, loading sequence and load interaction effects. Due to the uncertainty in fatigue design, it is difficult to accurately estimate the distribution of fatigue life. Until now, several stochastic methods were developed for cumulative damage estimation [8, 12-17]. For these methods, additional experimental data are often required and the uncertainties associated with external loadings are ignored. By using damage tolerance options to railway axles, Zerbst and Beretta et al. [1-2, 18-19] investigated the factors that influence the residual lifetime as well as the required inspection intervals. Beretta et al. [4, 8, 16] developed a probabilistic approach using the NASGRO crack growth equation and effects of corrosion on the fatigue behavior of A1N steel. Rathod et al. [15] presented a method for probabilistic modeling of fatigue damage accumulation using the Miner rule and a probabilistic S-N curve, which assumes the damage accumulation process as a linear phenomenon whereas for engineering components, their damage process is a nonlinear phenomenon.

During the probabilistic modeling of fatigue damage accumulation, two aspects need to be clarified [12, 17]: an accurate damage accumulation model and an uncertainty quantification method. The majority of research indicates that the uncertainty quantification process usually introduces complex mathematical calculations. In this paper, a simple approach is developed to characterize the stochastic fatigue damage accumulation of railway axle steels, which attempts to minimize the computational complexity and can be explained by well-known physical laws.

2. Probabilistic modeling of damage accumulation for fatigue reliability analysis

Varying loads often lead to a cumulative failure of railway axles. Cumulative damage is an irreversible degradation process throughout the axle life which ultimately causes failure [20]. Cumulative damage in engineering is generally introduced by fatigue, creep, corrosion, and wear, which are commonly used as a measure of degradation. Degradation paths evolve in the space of a degradation measure which evolves toward the failure threshold. Moreover, the axle life or reliability manifested as the degradation measure is deteriorating probabilistically with time, which can be graphically shown in Fig. 1.

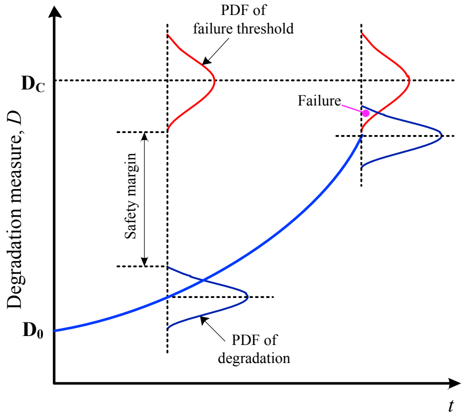

Fig. 1 Scheme of Degradation path

In Fig. 1, D_0 is the initial damage, D_C is the critical threshold which varies appreciably among samples in practice. Wang et al. [21] explained that the variability of degradation measure increases with time. As a measure of degradation, the cumulative fatigue damage under a given life is random, where the mean and variability increase with time. Since a large amount of scatters in fatigue data are observed, the number of cycles to failure at any given stress level can be treated as a normal or lognormal variable. Based on this, the cumulative fatigue damage is also a random variable.