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Development of probabilistic fatigue curve for asphalt concrete based on viscoelastic continuum damage mechanics

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Abstract

Due to its roots in fundamental thermodynamic framework, continuum damage approach is popular for modeling asphalt concrete behavior. Currently used continuum damage models use mixture averaged values for model parameters and assume deterministic damage process. On the other hand, significant scatter is found in fatigue data generated even under extremely controlled laboratory testing conditions. Thus, currently used continuum damage models fail to account the scatter observed in fatigue data. This paper illustrates a novel approach for probabilistic fatigue life prediction based on viscoelastic continuum damage approach. Several specimens were tested for their viscoelastic properties and damage properties under uniaxial mode of loading. The data thus generated were analyzed using viscoelastic continuum damage mechanics principles to predict fatigue life. Weibull (2 parameter, 3 parameter) and lognormal distributions were fit to fatigue life predicted using viscoelastic continuum damage approach. It was observed that fatigue damage could be best-described using Weibull distribution when compared to lognormal distribution. Due to its flexibility, 3-parameter Weibull distribution was found to fit better than 2-parameter Weibull distribution. Further, significant differences were found between probabilistic fatigue curves developed in this research and traditional deterministic fatigue curve. The proposed methodology combines advantages of continuum damage mechanics as well as probabilistic approaches. These probabilistic fatigue curves can be conveniently used for reliability based pavement design.

Keywords: Probabilistic fatigue curve; Continuum damage mechanics; Weibull distribution; Lognormal distribution

1. Introduction

Fatigue in asphalt pavement is one of the major distress mechanisms, which is primarily caused by repeated traffic loading. Initially, this damage starts with microcracks at locations of higher stress (or strain) concentration. These microcracks further coalesce into a series of interconnected macrocracks finally leading to failure of pavement. This degradation under cyclic loading has been characterized in laboratory conditions using various modes of loading including flexure [1,2], direct tension [3], indirect tension [4] and shear [5]. One common feature among all these loading modes is amplitude of strain (or stress) held constant throughout the fatigue testing and its response is recorded. The testing is continued until specimen fails completely. This process is repeated at other strain (or stress) levels to obtain relationship between strain (or stress) amplitude and number of cycles to failure. In general there are two different approaches used for fatigue life prediction i.e. phenomenological and mechanistic approaches.

In the phenomenological approach, a series of tests are performed at various conditions to capture all significant factors that contribute to the fatigue damage. Using the

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data generated, regression models are developed to relate fatigue life with other parameters like binder type, aggregate type and gradation, air voids and testing method. If one of the parameters is neglected initially, the entire set of experiments has to be repeated to capture its effect. Thus, careful attention is required while deciding on factors to be accounted, experimental plan and regression model. In this approach, fatigue damage process is considered as deterministic. Even under extremely controlled condition testing, fatigue test results developed show significant scatter/variability [6].

Alternatively, mechanistic approach is more complex which is applicable to a wide range of loading and environmental conditions. Some examples for mechanistic approach are Visco-Elastic Continuum Damage (VECD) approach, fracture mechanics, and micromechanics. VECD approach relates stress-strain using the principles of thermodynamics. In the VECD approach, a damaged body is represented by a homogeneous continuum where the scale of the test specimen is much larger than the defect size. These VECD models use macroscale observations to capture the net effect of microstructural changes. Hence, the VECD model is convenient for modeling overall behavior of the material. Present day VECD models consider material properties and damage process to be deterministic. Improper selection of input values in these VECD models will lead to significant deviation in predicted material behavior. Thus, extreme care has to be exercised while choosing input values for VECD model parameters. Probabilistic fatigue analysis can account for the variability issues like constituent materials, specimen fabrication issues, and testing practices. Therefore, there is a need of probabilistic approach for the fatigue life analysis within VECD framework.

This paper presents a novel methodology for predicting fatigue life of asphalt concrete for a given reliability based on elastic-viscoelastic correspondence principle and VECD mechanics. The paper is divided into 6 sections of which this is the first section. Research work conducted by others in area of asphalt concrete fatigue characterization, VECD mechanics, and probabilistic fatigue modeling is discussed in the second section. Details regarding asphalt concrete mixtures, and specimen preparation and testing is presented in third and fourth sections, respectively. The next two sections deal with the proposed probabilistic fatigue analysis methodology and a case study along with statistical analysis. The last section concludes the article.

2. Previous work

Various researchers have used regression-based approach to relate fatigue life (N_f) and initial strain amplitude (ε_0) as presented in Eq. (1) [7–10]. Due to its simplicity and ease of use, this empirical model is popular among engineering community. The regression coefficients (K and n) in Eq. (1) are specific to the asphalt mixture type, volumetric composition and binder type, and the test parameters used in the laboratory evaluation. A schematic diagram of fatigue curve developed after laboratory evaluation is shown in Fig. 1. Due to mechanical compliance of machine and pneumatic control issues, strain amplitude during fatigue testing is not exactly constant. This small variation in applied strain amplitude is specific to particular equipment in use. Thus, some scatter in strain amplitude (in vertical direction) in fatigue curve is expected. Further, variability in constituent materials, aggregate microstructure, and testing procedure use will contribute to inherent variability in failure point. Hence scatter in fatigue life (in horizontal direction) is always expected.

$$N_f = k_1 \left(\frac{1}{\varepsilon_0}\right)^{k_2} \tag{1}$$

where k_i = regression coefficients.

Several studies have reported that regression coefficients in Eq. (1) are found to be very sensitive to mixture properties. Navarro and Kennedy observed that the value of K generally ranges from 5.0×10^{-20} to 6.5×10^{-5} while value of n ranges between 1.2 to 6.3 [6]. Shukla and Das [11] reported that value of K varied between 5.35×10^{-18} and 497 while value of n ranged between 2.93 and 6.17. Navarro and Kennedy [6] have reported Coefficient of Variation (CV) values of fatigue life ranged between 26 and 84%. For field-extracted specimens, Monismith et al. [12] have reported CV values between 25% and 131%. Similarly for laboratory prepared specimens, CV values ranged between 54% and 76% [12–13]. Thus, it can be concluded that CV value for the fatigue life of field specimens is more when compared to laboratory prepared specimens.

Various researchers have reported scatter in fatigue life distribution. Miura [14], Tsai et al. [15], Sun et al. [16], Klemenc et al. [17] have noted that fatigue life distribution of bituminous mixtures follows Weibull distribution. Pell and Taylor [18] found that fatigue life follows lognormal distribution. Zhao et al. [19] found that fatigue life distribution at a given strain magnitude is skewed to the right.

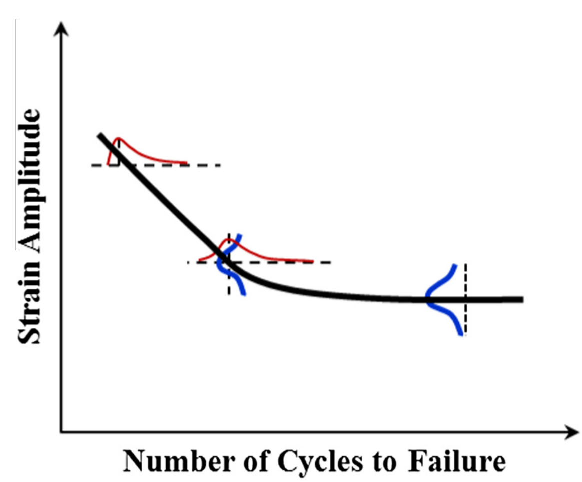

Fig. 1. Fatigue curve showing scatter in strain amplitude and fatigue life.