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Multi-scale model for linking collective behavior of short and long cracks to continuous average fatigue damage

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ABSTRACT

A multi-scale model is developed in this study for linking collective behavior of short and long cracks to continuous average fatigue damage. By using the developed model, the average fatigue damage evolution can be evaluated through some parameters that reflect collective behavior of short and long cracks, while collective behavior of short and long cracks can be reflected from the measured continuous average fatigue damage evolution based on the effective stress concept. The effectiveness of the model is verified by comparing numerical results with experimental data. The comparative results show that the developed model can be used to study the metal fatigue failure mechanisms from both macro- and micro-scale viewpoint.

1. Introduction

Fatigue fracture is one of most common failure modes for engineering structures [1,2], especially for steel structures, in which 80–90% of failures are due to fatigue fracture [3,4]. Therefore, fatigue failure of metals has been the subject of study by many researchers since Wöhler's research on the railways axles [5]. However, the understanding of fatigue mechanisms, for better evaluation of fatigue damage accumulation and fatigue life, is still a challenge task up to now. With the development of theory and framework of the continuum damage mechanics (CDM), probably first presented by Kachanov [6], and the advance in technique for micro-observation of interior structure of steel materials, such as scanning electron microscopy [7], the current methods for studying fatigue problems can be mainly classified into two categories based on whether looking at the problem from a larger macro- or smaller micro-scale viewpoint.

The first category of the methods pays attention to the use of a continuous average damage variable to describe degradation of material in a larger macro-scale, which is easy for engineering application due to its simplicity and effectiveness. Since Miner first expressed this concept in the description of fatigue damage accumulation in 1945 [8], the cumulative fatigue damage theories have been developed increasingly including the works of Marco and Starkey [9], Henry [10], Gatts [11], Manson [12], Chaboche [13] and many others. As a result, many different fatigue damage models have been developed based on the concept of CDM, e.g. Chaboche [13], Manson [14], Franke [15] and many others. A comprehensive review of cumulative fatigue damage theories for metals has been provided by Fatemi [16].

The second category of the methods pays attention to the study of fatigue crack behavior within material to understand fatigue failure mechanisms, especially for short fatigue cracks in micro-scale since the short-crack regime occupies a large

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Nomenclature

D	damage variable
a	crack length
d	grain size
n^{total}	total number of the grains within the concerned zone
S	total area of the concerned zone
n	number density of cracks
$a_{\max}$	maximum size of current cracks
N	number of cycles
N_f	number of cycles to failure
$\dot{n}_N$	crack nucleation rate
$\Delta\sigma$	stress range
$\Delta\gamma$	shear strain range
$\Delta\varepsilon$	axial strain range
$\dot{a}$	crack growth rate
P	probability that cracks terminate at grain boundary
$A, \alpha, B, \beta, C, a_0, E, q$	constants of model parameters

portion of total fatigue life [17–19], where the length of such cracks is comparable with microstructural dimension such as grain size for metals [20,21]. For long cracks, famous Paris' law is widely used to evaluate the remaining life of a component [22,23]. Since Pearson first found that short cracks grow much faster than long cracks and the threshold load for short cracks growth is more below than that for long cracks [24], the micro-analysis of fatigue mechanisms in metal materials in terms of short cracks behavior, has been one of main research topics for fatigue. Many short fatigue crack growth models for metal materials have been developed based on micro- observation of short fatigue cracks behavior, e.g. Miller [25], Delosrios [26], and Angelova [27]. Miller [28,29] and Hussain [30] provide comprehensive reviews on these models for describing behavior of short fatigue cracks. It shows that micro-structures in polycrystalline metals, such as grain boundaries, play an important role in short cracks nucleation and growth [31]. Short cracks keep nucleating and growing within grain domains, which seldom overcome grain boundary obstacles [32].

Nevertheless, for the first category of the methods, using a variable to describe the continuous average fatigue damage accumulation extent in a larger macro-scale cannot explain the fatigue failure mechanisms viewed from a smaller micro-scale, while for the second category of the methods, the micro-analysis of short fatigue crack behavior focusing on only a few single cracks cannot evaluate average fatigue damage extent in a larger macro-scale, which is difficult for engineering application. Actually the material fatigue damage is a multi-scale phenomenon before entering to long-crack stage, which covers overall deterioration behavior of the material in macro-scale and a large number of short cracks nucleation and growth in micro-scale. Therefore, this paper aims to develop a new multi-scale model for fatigue damage accumulation, which can describe both the average damage evolution reflecting the progressive degradation of material behavior and the collective behavior of internal cracks from a large number of short cracks initiation and growth to a few main long cracks. Although a multi-scale fatigue damage model had been developed in the previous work [33], it only focused on the collective behavior of short fatigue cracks in micro-scale. While the short-crack regime occupies a large portion of total fatigue life, long-crack regime shall not be neglected in the prediction of the total fatigue life [32,34]. The developed multi-scale model can overcome the current shortcoming, which can describe the relationship between the continuous average damage and collective behavior of both short and long cracks.

2. Definition of continuous damage variable by the number density of short and long cracks

The material deterioration due to fatigue actually depends on the collective evolution of a large number of internal cracks but not only a few single cracks, especially in the short-crack regime [35]. Therefore, in order to establish a variable to describe the average damage extent in the fatigue process, the damage variable D in the multi-scale fatigue model, should consider the collective effect of all current cracks within the concerned zone in an average way.

To explain how to establish the damage variable, let us see Fig. 1a and b. It can be seen from Fig. 1b that there are numerous short cracks in a smaller micro-scale which cause overall deterioration of the specimen in a larger macro-scale. In order to characterize the average damage extent due to collective evolution of internal fatigue cracks, the random micro-grain within the material is simplified into regular hexagon as shown in Fig. 1c as done in Ref. [36]. Based on the effective stress concept, as shown in Fig. 1c, the damage variable D_i for the ith micro-grain within the concerned zone, where exists a crack with length a_i can be expressed as:

$$D_i = \frac{a_i}{d} \tag{1}$$

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