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A novel two-scale damage model for fatigue damage analysis of transition region between high- and low-cycle fatigue

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ABSTRACT

In this study, a continuum damage mechanics-based method combined with a novel two-scale meso-mechanical model was proposed for modelling the fatigue damage evolution in metals, within the transition region. A representative volume element (RVE) consisting of a matrix and a microscopic inclusion was introduced to establish the damage-coupled constitutive equations of the material experiencing fatigue in the transition region. The Eshelby solution was adopted to obtain the elastic modulus deterioration of the RVE by using the damaged matrix and the inclusion. The ductile damage model of Lemaitre was applied to describe the damage evolutions of the matrix and the inclusion. The parameters in the damage evolution equations were determined from the fatigue test data. Then, these parameters were directly applied to the fatigue damage analysis of the transition region. The numerical simulation was executed using ABAQUS software, and the predicted results were in accordance with the experimental data. The proposed method provides a novel perspective to illustrate the mechanism of damage evolution within the transition region.

1. Introduction

High-cycle fatigue (HCF) and low-cycle fatigue (LCF) are two typical fatigue problems in engineering structures [1]. The number of cycles to failure is used as a criterion to define the types of fatigue. Fatigue is generally classified as LCF when the fatigue life is less than 10^4 cycles. In this case, the damage evolution is considered to be closely related to the macro-plastic deformation; thus, fatigue life is usually expressed in terms of plastic strain. Meanwhile, when the fatigue life is higher than 10^5 cycles, fatigue is classified as HCF. In this case, the damage evolution is governed by the stresses, and the expression of fatigue life is typically correlated with stress variables. According to the aforementioned classification, there is a fatigue region between 10^4 and 10^5 cycles which is usually referred to as the transition region. Essentially, at each of these three regions, the fatigue behaviour of the material is significantly different. However, the classification method in terms of fatigue life is phenomenological, and does not consider the intrinsic characteristics of the different fatigue damage processes.

In engineering applications, the prediction of the fatigue life of structures is always of primary concern. Based on experimental observations, the Coffin–Manson equation and the Basquin equation have been widely used for the evaluation of the fatigue life of structures under LCF and HCF conditions, respectively [2]. However, there are no recognised effective methods for the cases of fatigue life within the transition region. By combining the two aforementioned methods, the Manson–Coffin–Basquin equation [3] is formed, and the total strain–life curve of the material can be obtained. This equation can be used for the prediction of the fatigue life of the material under various load conditions. However, the results are only reliable for the cases of HCF and LCF. Moreover, the fatigue life within the transition region obtained through the abovementioned equation is a result of a mathematical compound method, and lacks a theoretical basis in terms of mechanics. Moreover, critical-plane methods are widely used in applications. Htoo et al. [4] studied the fatigue behaviour of TI-6AL-4V alloy within the transition region using the Smith–Watson–Topper (SWT) damage model. They found that the variation in the local stress ratio should be considered when predicting the fatigue life of notched specimens. However, the SWT method does not consider the variation in the stress ratio. Overall, several issues still remain to be resolved regarding the analysis of fatigue problems within the transition region through the use of traditional methods.

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Nomenclature

$\boldsymbol{A}^r$	strain localization tensor
$\boldsymbol{B}^r$	stress localization tensor
C_y^μ	micro-plasticity modulus
D^r	damage extent
$\boldsymbol{E}^r$	elastic modulus
F^D	damage dissipation function
$\boldsymbol{P}$	polarization tensor
$\dot{p}^r$	cumulative plastic strain rate
R	stress ratio
$\boldsymbol{S}$	Eshelby tensor
X^r	back stress
Y^r	strain energy release rate
ε_{ij}^r	strain tensor
ε_{eq}^r	equivalent strain
$\dot{\lambda}^r$	plastic multiplier rate
ν	Poisson's ratio
σ_{eq}^r	equivalent stress
σ_f^r	fatigue limit
$\sigma_{H,mean}$	mean hydrostatic stress
σ_{ij}^r	stress tensor
σ_m	mean stress
σ_{max}^{*r}	maximum equivalent stress
σ_y^r	yield stress

Superscript

r	represents the matrix phase m or inclusion phase μ

Damage-mechanics-based approaches are applied to fatigue problems as well. The deterioration of materials undergoing cyclic loading is described through damage variables [5]. The damage-coupled constitutive equations and damage evolution equations can be derived according to the theory of thermodynamics. For the HCF cases, Chaboche [6] and Xiao et al. [7] proposed continuous damage mechanics models, and achieved good agreement between the predicted life and the experimental data. Ottosen et al. [8] presented a simple and appealing model, which is based on the concepts of a moving endurance surface and an evolving damage variable. This model can consider both uniaxial and multiaxial stress states. Stephanov et al. [9,10] computed damage accumulation by means of an integral directly on the non-radial arbitrary path to study multiaxial fatigue. For the LCF cases, Lemaitre and Desmorat [11] proposed a simple damage model considering the cumulative plastic strain; their model can be considered to be an extension of the ductile damage model. These contemporary fatigue damage models are well able to describe the damage-evolution processes and to predict the fatigue life for the HCF and LCF cases. However, for the fatigue problems within the transition region—in which plastic strain and elastic strain magnitudes equally contribute to the total damage—the separated cumulative plastic strain-based model or the stresses-based model cannot reasonably capture the nature of damage evolution. Thus far, two types of methods have been developed to address this issue. Kang et al. [12] maintain that the total damage can be divided into elastic damage and plastic damage. When the plastic strain is very small, fatigue damage is mainly attributed to elastic damage, which corresponds to the HCF phenomenon. When the plastic strain significantly increases and plastic damage prevails over elastic damage, the plastic damage will account for the fatigue failure, which corresponds to the phenomenon of LCF. Furthermore, the damage value of the transition zone was assumed to be equal to the superimposition of the two types of damage. However, the authors did not explain why they assumed linearity. Shen et al. [13] calculated both the elastic damage and the plastic damage; then, after comparing the two damage values, they selected the greater one as the damage extent of the material. This method can be approximated as an algorithm for calculating the damage when either the elastic damage or plastic damage accounts for the greatest part of the total damage. However, when the elastic strain and plastic strain level cause an equivalent level of damage, the elastic damage and the plastic damage simultaneously exist and interact during the evolution. Therefore, it would be unreasonable to only consider one type of damage. Although the predicted results obtained from the aforementioned models agreed well with the experimental results for certain cases, there is a lack of sufficient theoretical works on the mechanism of fatigue damage occurring within the transition region.

The macro-mechanics models completely separate HCF from LCF by using the distinct formulations of fatigue life; therefore, it is difficult to establish a model of sound physical meaning for the transition region. Micro-mechanics models offer the possibility of establishing an approach which would illustrate the damage mechanism at all stages in a relatively natural manner. In the studies of composite materials, first, the theory of a multi-scale model was adopted [14–16], such as the current application of the Kröner [17] model, Hill's incremental model, and the secant, tangent and affine formulations. In addition, micro-mechanics models can be used for the analysis of metal materials. For this case, the matrix and the inclusions are not necessarily the actual components, as in the composite materials; instead, they should be considered as fictitious parts, for the purpose of modelling the mechanical behaviour of the material. During the past recent decades, multi-scale models have raised concerns in the research of fatigue problem. Desmorat et al. [18] employed the Eshelby–Kröner scale transition law, and used a double-scale model to describe the HCF phenomenon in which damage occurs only at the microscopic scale. Wan et al. [19] considered the phenomenon of building orientations and porosity in the additive manufacture structures, and used the meso-scale damage-evolution equation to describe the damage evolution process at the macroscopic scale; their findings agreed well with the experimental results. However, the reports found on the study of fatigue within the transition region were scarce.

This study aims at presenting a novel two-scale damage model to illustrate the fatigue damage evolution of metals in the transition region. A new two-scale representative volume element (RVE) model was established to describe the constitutive equations of the matrix phase and those of the inclusion phase. The damage evolution model for the material experiencing fatigue within the transition region was derived. The parameters presented in the equations of damage evolution of the matrix and of the inclusion were determined from the fatigue test data. Finally, the numerical simulation was executed in the ABAQUS software; the predicted results agreed well with the experimental data. Compared with the existing models, the proposed model has an advantage of considering the coupling effect between elastic damage and plastic damage in transition region. In addition, both the elastic and plastic damage models are derived from a unified ductile damage model, which reduces the number of parameters and simplifies the parameters calibration.