European Journal of Mechanics A/Solids 60 (2016) 183–195

Contents lists available at ScienceDirect

European Journal of Mechanics A/Solids

journal homepage: www.elsevier.com/locate/ejmsol

Continuum approach for modelling transversely isotropic high-cycle fatigue

Sami Holopainen*, Reijo Kouhia, Timo Saksala

Tampere University of Technology, Department of Mechanical Engineering and Industrial Systems, P.O. Box 589, FI-33101, Tampere, Finland

ARTICLE INFO

Article history:
Received 3 December 2015
Received in revised form
27 May 2016
Accepted 17 June 2016
Available online 29 June 2016

Keywords:
High-cycle fatigue
Transversely isotropic fatigue
Endurance surface
Out-of-phase loading

ABSTRACT

A continuum approach is proposed for modelling multiaxial high-cycle fatigue of solids which exhibit transversely isotropic fatigue properties. The approach is an extension of the original isotropic model proposed by Ottosen, Stenström and Ristinmaa in 2008, which model is based on the concept of a moving endurance surface in the stress space and on an evolving damage variable. The theory is formulated in a rate form within continuum mechanics framework without the need to measure damage changes per loading cycles. Capability of the approach is illustrated by several examples with different uni- and multiaxial loading histories.

© 2016 Elsevier Masson SAS. All rights reserved.

1. Introduction

Design against fatigue constitutes an integral part of mechanical engineering analysis. Examples of mechanical components that experience fatigue during their service life are axels in motors, railroad wheels, aircraft components, crankshafts, propellor shafts, and turbine blends to mention a few. As expressed by Bolotin (1999), in the narrow sense the term fatigue of materials and structural components means damage and fracture due to cyclic, repeatedly applied stress. It has been recognized in practise that the fatigue stress conditions are often multiaxial consisting of combined bending and twisting, and the conditions can additionally be of out-of-phase and subjected to different frequencies. Under those alternating complex loadings, material fails at stress levels substantially lower than observed under monotonic loadings. To understand and model fatigue phenomena under different loading situations, knowledge from materials science and mechanics of solids is mandatory, cf, e.g. Suresh (1998), Murakami (2002).

High-cycle fatigue, which typically occurs when the loading consists more than of 10^4 cycles and the macroscopic behaviour of the material is primarily elastic, is influenced by several factors such as surface roughness, grain size and distribution as well as cleanliness of material, cf. Morel (2001), Morel et al. (2001), and Makkonen et al. (2014). Subjected to those metallurgical variables, material undergoes fatigue damage which is associated to degradation of material properties due to initiation, growth, and coalescence of microdefects. If the defects in the material are assumed to be distributed in a statistically homogeneous manner then it is advantageous to model the fatigue mechanisms within continuum mechanics framework. The specific features with regard to continuum damage mechanics and fatigue are discussed e.g. in Paas et al. (1993) and Wang and Yao (2004). Moreover, the fundamental ingredients of dynamic failures, high-cycle fatigue, ductile failure, and failure of brittle and quasi-brittle materials are found e.g. from McDowell (1996), Lemaitre and Desmorat (2005), Desmorat et al. (2007), and Murakami (2012).

Basically three stages can be identified in the process of fatigue failure, cf. Lemaitre (1984), Suresh (1998), Morel et al. (2001): (i) nucleation and growth of micro-cracks and voids due to local inhomogeneities and local micro-plastic effects terminating in the creation of macro-cracks; (ii) stable crack propagation phase; (iii) unstable crack propagation phase leading to failure. In uniaxial fatigue tests, the phase (ii) can further be divided into two stages: (a) crack growth on a plane of maximum shear and (b) crack propagation normal to the tensile stress. However, most of the fatigue life is spent in the stage (i). The goal of the present work is to find a representative continuum-based model capable to predict macroscopic mechanical behaviour which mainly results from micro-cracking during the first stage (i). In contrast to the last two stages which are dominated by macro-cracks, the first stage is

---

* Corresponding author.
E-mail address: sami.holopainen@tut.fi (S. Holopainen).

http://dx.doi.org/10.1016/j.euromechsol.2016.06.007
0997-7538/© 2016 Elsevier Masson SAS. All rights reserved.

governed by statistically distributed micro-mechanisms. Due to this characteristic, linear fracture mechanics cannot be applied in the first stage.

Different approaches for fatigue analysis exist, cf. Sines (1955), Findley (1959), Dang Van et al. (1989), Dang Van (1993), Palin-Luc and Lasserre (1998), Papadopoulos (2001), Socie and Marquis (2000), Zouain and Cruz (2002), Liu and Zenner (2003), and Zhang et al. (2012). Since entire high-cycle fatigue process relies on brittle damage mechanisms, strain controlled approaches suitable for ductile damage behaviour cannot be directly applied, and stress-based approaches are preferred, cf. Ottosen et al. (2008). Majority of those approaches represents fatigue-limit criteria, cumulative damage theories, and cycle-counting methods. Among fatigue-limit criteria, critical plane approaches have gained a large popularity meanwhile equivalent, invariant, and average stress approaches represent other prominent examples in more early stage on the research.

According to critical plane approaches, fatigue life is controlled by combined action of alternating shear stresses and the normal stress acting on a plane. This plane, which is termed the critical plane, varies between models. Perhaps the pioneering model by Findley (1959) is one of the most used high-cycle fatigue criterion.

One more recent state-of-the-art example of critical plane approaches is the multiaxial fatigue criteria model for metals given by Liu and Mahadevan (2007). Other representative approaches are found e.g in Matake (1977), Dang Van (1993), Carpinteri and Spagnoli (2001), and Papadopoulos (2001).

Two shortcomings of the critical plane approaches are the inability of the defined critical plane to follow crack initiation realistically and the restriction only to a certain set of material parameters. The latter feature is due to a critical plane which only accounts for the stress state, but not material properties.

All the previously mentioned invariant based and critical plane fatigue-limit criteria describe the fatigue limits under infinite number of identical cycles. However, for finite life predictions those models are equipped with cumulative damage theories, which describe the damage increase per cycle. Due to this characteristic, the loading is required to consist of well-defined cycles. Probably the best known model among the cumulative damage theories is the Palmgren-Miner model.

To model fatigue under complex load histories, cycle-counting methods need to be applied so as to define equivalent, representative cycles. However, definition of equivalent cycles from a complex load spectrum is a challenging task which feature makes the cycle-counting approaches difficult to apply in practice.

A notable contribution for general computational high-cycle fatigue analysis is given by Peerlings et al. (2000), who proposed a continuum damage model for the prediction of crack initiation and propagation. They also showed that the damage growth localizes in a vanishing volume which is due to the singularity of the damage rate at the crack tip. To remove the damage rate singularity, Peerlings et al. (2000) proposed a gradient-enhancement to their constitutive model. More recent investigations of gradient effects on fatigue are found e.g. in studies by Askes et al. (2012) and Luu et al. (2014).

Although a multitude of models for multiaxial fatigue damage have already been proposed, many of them are not able to predict fatigue under complex and out-of-phase loadings well. Many models in the early stage in the research cannot satisfactorily represent the fatigue life for more than 10^6 either, or they initially are conceived only for in-phase cyclic stresses, i.e. proportional cyclic loadings are required. Reviews and comparisons of different high-cycle fatigue models can be found in studies by Papadopoulos et al. (1997), Ding et al. (2007), Kenmeugne et al. (2012), and Lorand (2012). Furthermore, research related to anisotropic fatigue models has mainly been focused on uniaxially reinforced, transversely isotropic composites for which the elasticity properties also are transversely isotropic, cf. Robinson and Duffy (1990); Robinson et al. (1990); Arnold and Kruch (1991); Kruch and Arnold (1997). Although mechanical behaviour of many materials can be considered elastically isotropic, their fatigue properties may differ in different directions. An example of such material is forged steel whose fatigue properties are transversally isotropic. Majority of the models discussed above cannot be applied to the modelling of anisotropic fatigue behaviour or they are formulated using cycle-counting methodologies generally unsuitable in demanding practical applications.

An appealing model for high-cycle fatigue suitable for arbitrary multiaxial loadings was proposed by Ottosen et al. (2008). In their approach, the concept of a moving endurance surface in the stress space is postulated together with a damage evolution equation. Movement of the endurance surface is modeled with a reduced deviatoric stress measure which defines the center of the endurance surface in a similar way than the back-stress tensor in plasticity, thus memorizing the load history. Damage evolution is activated whenever the stress state is outside the endurance surface, and the time rate of the endurance surface is positive. In this model, uniaxial and multiaxial stress states are treated in a unified manner for arbitrary loading histories, thus avoiding cycle-counting techniques. Therefore, the approach by Ottosen et al. (2008) could be described as an evolution equation based fatigue model. It has been also used in a recent study by Brighenti et al. (2013). Similar features can also be observed in the approaches proposed by Peerlings et al. (2000), Morel et al. (2001), and Zouain et al. (2006).

In this paper, a transversely isotropic high-cycle fatigue model is presented. Consistent with the Ottosen et al. (2008) approach, the proposed model is formulated using evolution equations which feature makes the definition of damage changes per cycle redundant, i.e. cycle-counting techniques do not need to be applied. Compared to preceding approaches of similar concept, the model uses only macroscopical quantities, which property makes the model simpler.

2. The model

2.1. Isotropic high-cycle fatigue (HCF) model

In this section, the model concept of the approach developed by Ottosen et al. (2008) for isotropic solids is briefly summarized. The model uses only macroscopical quantities, and the constitutive response is assumed to be purely elastic, which is a relevant feature in macroscopic HCF-modelling. It is well known that the endurance limits of a material change with load conditions and that loading within these limits do not necessarily result in damage development. Based on these features Ottosen et al. (2008) postulated an endurance surface β in the stress space as

$$\beta = \frac{1}{S_0}(\bar{\sigma} + AI_1 - S_0) = 0. \qquad (1)$$

Denoting the stress tensor as $\boldsymbol{\sigma}$, the first stress invariant is given by $I_1 = \operatorname{tr}\boldsymbol{\sigma}$. The invariant I_1 reflects the effect of the mean stress, i.e. the hydrostatic tension enhances the fatigue development while fatigue is suppressed under hydrostatic compression. The parameter A is considered as positive and non-dimensional, and can be associated in uniaxial cyclic loading as the slope of the Haigh-diagram. The last parameter S_0 is the endurance limit for zero mean stress. The effective stress present in (1) is defined in terms of the second invariant of the reduced deviatoric stress $\mathbf{s}-\boldsymbol{\alpha}$ as

Download English Version:

https://daneshyari.com/en/article/7170339

Download Persian Version:

https://daneshyari.com/article/7170339

Daneshyari.com