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Review of fatigue crack growth under non-proportional mixed-mode loading

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ABSTRACT

Cyclic non-proportional loading is common experimental practise for investigations of large structures like vehicles. Numerical analysis of local non-proportional loading conditions is also a well established field of research and application. However, theoretical and practical support is rare for evaluating the growth of fatigue cracks under non-proportional cyclic loading conditions. At least seven influence factors – most of them not yet thoroughly understood – are listed and discussed in the paper: the mode-mixity, the material's influence including its anisotropy if existent, the degree of cyclic plastic deformation and its direction ahead of the crack tip, the crack closure phenomenon, the related mean stress effect, the component's geometry in general and especially the variable mode-mixity along a crack front. Two crack propagation mechanisms must be considered: (a) the tensile stress dominated, mode II minimising mechanism and (b) the shear stress dominated mechanism. Transition mode-mixities are observed. Some successful explanations of experimental findings have been published, however, a generally accepted and validated formulation of a crack driving force parameter has not yet been identified.

1. Introduction

Most of the engineering structures and components are subjected to fatigue load conditions, which are a combination of various load sequences originated from different sources. Only in rare cases, a correlation of these load sequences may be observed. For ground vehicles, for example, the excitation provided by the roadway surface is uncorrelated with load sequences from manoeuv-ring, be it curving or acceleration and braking. After an onset of fatigue damage – for metallic materials this generally means the initiation of a fatigue crack – the crack is cyclically loaded in a way such that at the crack front non-proportional mixed-mode situations will occur.

In experimental investigations of the fatigue strength of such structures, it is common state of the art to reproduce the action of various load sequences in their realistic interconnection in a laboratory. Chassis and suspension test systems, for example, with twelve or more actuators simultaneously loading the structure are common practice in vehicle test laboratories.

In numerical fatigue life assessments, methods for dealing with the initiation of fatigue cracks are available even for the complicated non-proportional cases of combined cyclic loading. The accuracy of the fatigue life estimates obtained by applying these methods and the associated software tools are still under thorough investigation. Nevertheless, the engineers responsible for the fatigue strength of the structures are supported by these helpful numerical tools.

Already a remarkable number of systematic investigations of crack initiation lives under combined cyclic tension and torsion is available. Especially the 90° out-of-phase loading shows significantly different lives compared to the proportional loading. Fatigue lives under proportional and non-proportional loading (data mainly collected by Döring [1]) are reported in Table 1 (see also references [2–13]). A phase shift from in-phase loading to out-of phase loading leads to an increase in fatigue life if the test is performed in a stress or load controlled condition. According to Sonsino [14] this increase may by explained by a smaller local cyclic plastic deformation when load maxima do not coincide. In contrast to this, under strain controlled test, the fatigue life decreases under out-of-phase loading compared to in-phase loading. However, the material also plays an important role. The above statement holds for ductile materials whereas for semi-ductile materials a life reduction in strain-controlled condition could not be observed.

The orientation of initiated cracks can be estimated by applying critical plane approaches. Numerous papers have been published on this topic and only some references are given here, [15–20]. Approximation algorithms for calculating local non-proportional stress and strain sequences resulting from combined loading are available [21,22]. If the same non-proportional load sequence continues to be applied to the structure with a short fatigue crack the mode changes are evolving continuously.

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Table 1
Comparison of fatigue lives under proportional and sinusoidal non-proportional 90° out-of-phase loading (collected mainly by Döring [1]).

Material	N_{90°/N_{0° under stress control	N_{90°/N_{0° under strain control	Reference
C39	0.1	–	Tipton and Nelson [2]
S460N	10–20	0.21–0.28	Hoffmeyer et al. [3]
S460N	2–3	0.3	Sonsino [4]
CK45	0.4	–	Sonsino and Küppers [5]
SAE1045	5	–	Pan et al. [6]
25CrMo4	0.6	–	Grün et al. [7]
30CrNiMo8	1.1	0.4	Sonsino [4]
X6CrNiNb18–10	–	0.54–1.4	Hoffmeyer et al. [3]
X6CrNiTi18–10	3.8	0.5	Hug [8]
X10CrNiTi8–9	1.1	0.5	Sonsino [4]
AlMg4.5Mn	1	0.77–0.9	Hoffmeyer et al. [3]
Al6061 T6	–	0.2	Xia and Ellyin [9]
AlMgSi1	–	0.5	Ahmadi et al. [10]
AZ91	–	3–4	Renner [11]
Ti6Al4V	–	0.1	Nakamura et al. [12]
SAE1045	–	0.17–2.81	Fatemi and Socie [13]

The total life is the sum of the lives to initiate a crack of technical size and for subsequent fatigue crack growth. The previous comments on the crack initiation life are supposed to show that a lot of successful research has been done for non-proportional fatigue concerning the initiation stage. By contrast, investigations concerning the fatigue crack growth stage are still rare and isolated. In the following only the effect of non-proportional mixed mode loading in the fatigue crack growth stage will be reviewed.

The theoretical and practical support is immediately lacking as soon as the growth of fatigue cracks under non-proportional cyclic loading conditions is a matter of concern. A great discrepancy exists between experimental and numerical feasibilities of performing a proof of structural durability under these conditions. The topic of non-proportional mixed-mode fatigue crack growth has, however, become a field of scientific interest. The intention of this paper is to provide a collection of references to already investigated cases, the experimental observations and the analytical and numerical models developed therein. A list of items influencing the fatigue crack growth is gathered.

2. Mixed-mode fracture criteria

An early hypothesis for mixed-mode fracture was published by Erdogan and Sih [23]. Their maximum tangential stress criterion postulates that a mixed-mode loaded crack extends in the direction perpendicular to the maximum tangential stress ahead of the crack tip. The stress involved is usually calculated for linear elastic conditions and only the near crack tip asymptotic singular stress field is exploited. Shih [24], however, extended the maximum tangential stress criterion to elastic–plastic analyses for strain hardening material. Sih [25] further proposed the strain energy density criterion according to which crack extension in the direction of the minimum strain energy density is assumed. Another energy-based approach was developed by Hussain et al. [26] who made the maximum energy release rate of a kinked crack responsible for fracture propagation. All of the hypotheses listed so far predict very similar directions of a growing crack under mixed-mode I and II conditions. In the case that any of the aforementioned hypotheses is applied for fatigue crack growth analysis, the crack path is predicted such that the mode II loading at the crack tip is minimised.

A completely different path is obtained by the maximum shear stress criterion [27,28]. This criterion is especially useful in some cases when a crack subjected to mixed-mode I and II loading may remain or turn to propagate in a direction collinear with the plane of the maximum shear stress rather than the plane perpendicular to the maximum normal stress. Such a fatigue crack growth behaviour is observed, for example, during stage I of microstructurally short cracks as well as under enforced severe cyclic plastic deformation of notched axis-symmetric shafts under torsion. This initial list of most relevant mixed-mode fracture criteria is concluded with reference to extensive literature surveys of mixed-mode fatigue crack growth under proportional [14,29,30] and non-proportional loading [31].

3. Observations of fatigue cracks growing under non-proportional loading

Superimposing non-proportional mixed-mode conditions may be performed in innumerably different ways. The available test rig is the limiting feature for the choice of non-proportional load sequences. By using a uniaxial testing machine, the only possibility is to change the crack tip loading mode (or the mode-mixity) abruptly by changing the specimen's fixing conditions. Investigations on mode I pre-cracked specimens which are subjected to a mode-mixity, that is $\tan \Phi = \Delta K_{II}/\Delta K_I$ different from zero,may be seen as being investigations on non-proportional mixed-mode loading concerning the early growth after the mode-mixity change.

3.1. Abrupt change of the mode-mixity

The crack growth rate for the non-proportional first cycle after a mode-mixity change is experimentally inaccessible. The investigations focus on the crack deflection angle from the direction of the pre-crack grown under pure mode I. Since the early investigation of Iida and Kobayashi [32] the majority of experimental results [29,30] show a crack turning or kinking towards a path minimising ΔK_{II} which may be well described by the maximum tensile stress criterion. However, Roberts and Kibler [33] found cases for which the maximum tensile stress criterion was not valid. For high mode-mixities (with the original mode I pre-crack) coplanar fatigue crack growth was observed. In descriptions of these observations, the maximum shear stress criterion must be called. Besides the mode-mixity, this behaviour seems to be dependent on the material under investigation. No clear classification is available today with respect to which materials show preferred obedience to a mixed-mode criterion deviating from the popular maximum tensile stress criterion and its close relatives, strain energy density and energy release rate criterion. A third factor influencing the fatigue crack growth behaviour must be emphasised: the coplanar nearly maximum shear stress driven fatigue crack growth behaviour is observed preferably for higher stress intensity factor ranges. At the same time, this means that larger and more extended cyclic plastic deformations occur in the vicinity of the crack tip. Plastic deformations in metals – when observed on the microscopic scale – are dislocation motions in planes with high shear stresses. It seems that these planes provide the opportunity for crack extension. Even under the conventional mode I fatigue crack growth situation, the micro-mechanism of crack extension is explained by shear bands deviating from the mode I plane [34]. Eventually, at high mixed-mode stress intensity ranges, one shear plane remains dominating and the fatigue crack stays in this plane. For these cases, even crack growth rate data can be acquired. A mixed mode stress intensity factor range ΔK_{MM} was introduced replacing the conventional stress intensity factor range in a crack growth rate equation:

$$\frac{da}{dn} = C(\Delta K_{MM})^m. \qquad (1)$$