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Fatigue life estimation for multiaxial low-cycle fatigue regime: The influence of the effective Poisson ratio value

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ABSTRACT

A critical-plane criterion for multiaxial fatigue regimes characterised by low number of stress cycles is discussed. Such a criterion is formulated in terms of strains, by obtaining the displacement components acting on the critical plane from the strain tensor and, then, by considering an equivalent strain as a parameter to quantify the fatigue damage. Since the metallic materials generally behave in a plastic manner in low-cycle regime, the effective Poisson ratio has to be taken into account when defining the strain tensor. The theoretical results are here determined by varying the value of such a parameter in order to assess its influence on the fatigue life estimation. The effectiveness of the criterion is evaluated through experimental data related to fatigue tests on metallic hollow specimens under biaxial fatigue.

1. Introduction

As is well-known, propagation of cracks in metals occurs in one of these three fundamental ways: (1) cleavage fracture, (2) intergranular fracture (both of them named brittle fracture), (3) ductile tearing (also named ductile fracture). The type of fracture mechanism depends on the kind of loading, environmental conditions and material [1,2].

Cleavage and intergranular fracture are usually associated with little plastic deformation, due to a simple breaking of atomic bonds [3,4]. In the literature, different models describing cleavage fracture have been developed in the last decades, and an interesting discussion is reported in Ref. [5].

Ductile tearing is usually associated with a large amount of plastic deformation. In this case, the propagation of a crack is caused by merging of voids (i.e. by growth and coalescence of voids) due to atom movements driven by localised plastic deformation. Continuous efforts have been made related to the numerical simulation of ductile fracture using either coupled or uncoupled models [6].

Brittle fractures are invariably stress-controlled since they involve breaking atomic bonds, while ductile fractures are invariably strain-controlled since they involve slip mechanisms. As far as fatigue strength (or life) evaluation of structural components is concerned, the similarity between high-cycle fatigue (HCF) and brittle fracture on one hand and that between low-cycle fatigue (LCF) and ductile fracture on the other hand have been taken into account in many criteria [7].

In particular, several criteria for multiaxial fatigue propose to reduce the complex multiaxial stress/strain state to an equivalent uniaxial condition [8,9]: they are stress-based in HCF since the crack propagation phenomenon is stress-controlled in this former case, whereas they are strain-based in LCF since the crack propagation phenomenon is strain-controlled in the latter case.

Such criteria can be categorised as follows: methods based on stress invariants [10–12] or strain invariants [13,14], strain energy [15–20], critical-plane approach [21–34], space average of stress [35,36] and strain [37–41], whereas the first multiaxial criteria proposed in the literature are extensions of classical static multiaxial ones [8].

In multiaxial LCF regime, such extensions are: the criterion of the maximum principal strain, that of the maximum shear strain (Tresca criterion), and that of the maximum octahedral shear strain (von Mises criterion). Multiaxial LCF criteria that employ the concept of the ‘critical plane’ are very effective, since such a concept is based on the nucleation and early growth mechanism of fatigue cracks. Such criteria can estimate the fatigue life through an equivalent strain defined by using a combinations of shear and normal strain on the critical plane, but criteria formulated in terms of both stress and strain are also available in the literature [8,9].

In the present paper, the LCF criterion proposed in Refs. [32,33] is employed, the critical plane orientation being connected with the material plane which undergoes the maximum principal strain during the observation time interval. The strain tensor related to a given material point where to apply such a criterion is used to

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Nomenclature

$Prtz$	fixed frame
$P123$	principal strain axes frame
t	time
T	period
$\mathbf{w}$	unit vector normal to the critical plane
β	phase angle between longitudinal (axial) normal strain ε_z and shear strain γ_{zt}
γ_a	Manson–Coffin shear strain amplitude
$\gamma_{zt}(t)$	applied shear strain
$\boldsymbol{\varepsilon}$	strain tensor at material point P
$\varepsilon_{eq,a}$	equivalent normal strain amplitude
ε_a	Manson–Coffin normal strain amplitude
$\varepsilon_z(t)$	applied longitudinal (axial) normal strain
$\nu_{eff,A}$	analytical effective Poisson ratio
$\nu_{eff,l}$	literature effective Poisson ratio
$\nu_{eff,n}$	numerical effective Poisson ratio
$\boldsymbol{\eta}_P$	displacement vector at material point P, related to the critical plane
$\boldsymbol{\eta}_N$	normal displacement vector component of $\boldsymbol{\eta}_P$, acting on the critical plane
$\boldsymbol{\eta}_C$	tangential displacement vector component of $\boldsymbol{\eta}_P$, acting on the critical plane
$\phi,\ \theta,\ \psi$	principal Euler angles

Subscripts

a	amplitude
A	analytical
C	tangential
eff	effective
l	literature
m	mean value
max	maximum value
n	numerical
N	normal

compute the principal strain directions and the corresponding principal strains at each time instant.

Since the material has generally a plastic behaviour in low-cycle regime, the effective Poisson ratio ν_{eff} has to be evaluated. Accordingly, this paper is focused to the analysis of the effective Poisson ratio influence on the fatigue life estimation. Three methods are here applied to determine such a parameter: (i) analytical approach; (ii) non-linear finite element analysis; (iii) assumption of a constant value equal to 0.5.

Displacement components (normal and tangential) acting on the critical plane are then considered to compute an equivalent strain as the parameter to quantify the fatigue damage. Using the three above methods to determine ν_{eff}, the effectiveness of the above criterion is evaluated in terms of fatigue life estimation by comparing the theoretical results with biaxial fatigue experimental data found in Refs. [42,43].

2. Framework of the proposed criterion

Fig. 1 shows the algorithm of the strain-based criterion proposed to estimate the fatigue life of structural components under LCF regime. All the steps reported in Fig. 1 are discussed in the following Sections.

2.1. Determination of the effective Poisson ratio and strain tensor

At first (*Step 1* in Fig. 1), the effective Poisson ratio ν_{eff} has to be determined because, in presence of localised plastic deformations (as those in LCF regime), its value depends on the stress/strain history related to the material point (of the structural component being examined) where the fatigue analysis is performed.

In order to evaluate such a parameter, three different strategies can be employed. More precisely:

(i) Analytical approach (analytical effective Poisson ratio, $\nu_{eff,A}$), by decomposing the total normal strain, ε, in the elastic component, ε_e, and the plastic one, ε_p:

$$\nu_{eff,A}.\varepsilon = \nu_e.\varepsilon_e + \nu_p.\varepsilon_p \tag{1}$$

being ν_e the elastic Poisson ratio and ν_p the plastic one. Note that, in such a case, both the histories (plastic and total) related to the normal strain and the corresponding stress history, at the material point being examined, have to be measured.

(ii) Numerical formulation (numerical effective Poisson ratio, $\nu_{eff,n}$), by employing a numerical method to perform a non-linear analysis. Note that, in such a case, only the stress or strain history (applied to the structural component) has to be known.

(iii) Assumption of a constant value. The value 0.5 is often used in the literature (literature effective Poisson ratio, $\nu_{eff,l}$).

Generally, the material point P (of the structural component), where the fatigue analysis is performed, is located on the external surface of the body. If the structural component is subjected to strain-controlled synchronous constant-amplitude cyclic tension and torsion (Fig. 2):

$$\varepsilon_z(t) = \varepsilon_{z,a} sin\left(\frac{2\pi t}{T}\right) + \varepsilon_{z,m} \tag{2a}$$

$$\gamma_{zt}(t) = \gamma_{zt,a} sin\left(\frac{2\pi t}{T} - \beta\right) + \gamma_{zt,m} \tag{2b}$$

the strain tensor $\boldsymbol{\varepsilon}(t)$ at point P (*Step 2* in Fig. 1), with respect to the reference system $Prtz$, is given by:

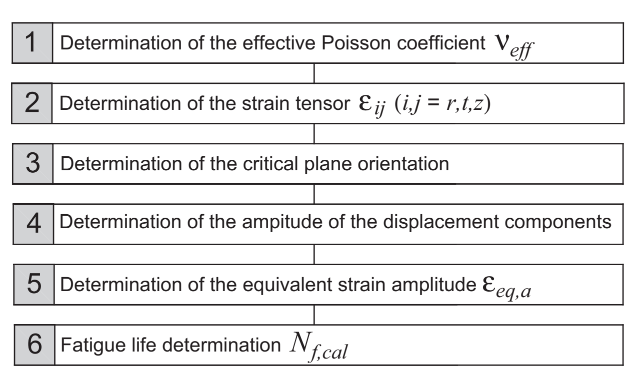

Fig. 1. Algorithm for fatigue life determination using the strain-based criterion proposed.