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A stress gradient approach for fretting fatigue assessment of metallic structural components

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ABSTRACT

In the present paper, the fretting fatigue life assessment of metallic structural components under cylindrical contacts is performed by applying a critical plane-based multiaxial fatigue criterion. Such a criterion is formulated by using the so-called critical point method: a material point located at a certain distance from the hot-spot on the contact surface is assumed to be the critical point where to perform the above assessment. The above distance, function of the material properties, is measured along three alternative paths (a normal path, an inclined path and a principal stress oriented path) and, using such three different paths to determine the critical point location, the effectiveness of the criterion is evaluated by means of experimental data related to aluminium alloy specimens under cylindrical contacts. Further, in order to improve the accuracy of the critical plane-based criterion in terms of fretting fatigue lifetime evaluation, a new approach involving a critical distance also function of the stress gradient in the contact zone is proposed and experimentally validated.

1. Introduction

Fretting is defined as a phenomenon that occurs at the contact interface between two assembly components, under a loading that gives rise to a slight oscillatory relative displacement of the friction surfaces being in contact [1]. Fretting fatigue occurs when a cyclic bulk fatigue loading is applied to one or both of the components of the assembly [1].

Depending on the relative displacement amplitude, two main regimes can be defined [2]:

(i) In large displacement range condition (gross slip contact condition, where slips are generally between 20 and 300 μm), the full sliding regime (i.e. full sliding condition operates through the interface) induces wear (permanent material loss) of the surface layers in contact;
(ii) In low displacement range condition (partial slip contact condition, where slips are generally between 3 and 20 μm), the partial sliding regime (i.e. the contact displays both stick and slip zones) induces severe stress gradients at the contact zone. Such a regime acts as a stress raiser, being the stress concentration significantly higher than that observed in the vicinity of a classical notch [3]. The high stress gradients over a volume (in the contact region) together with the cyclic nature of the bulk loading lead to the accumulation of damage in such a region, producing initiation of micro-flaws that further propagate evolving in a leading crack up to failure if the fatigue loading is sufficiently severe [4]. In particular, several studies show that most failures occurring under high-cycle fatigue present a large portion of life (up to 90% in some cases) spent for crack initiation in the region where stress state is governed by contact conditions, while only a very small fraction of fatigue life is spent in crack propagation away from such a region [5].

Square and open fretting loops are related to a gross slip condition, whereas closed and narrow fretting loops correspond to a partial slip condition (Fig. 1).

For case (i), dominant damage consists in a large amount of material removal and debris formation and, therefore, the phenomenon is named fretting wear [6]. The phenomenon related to case (ii), where dominant damage consists in a reduction of fatigue life compared to that of classical fatigue testing, is named fretting fatigue [6].

In the present paper, the criterion proposed in Ref. [7] is employed in order to estimate the crack initiation life of fretting high-cycle fatigued structural components. Such a criterion [7] is a reformulation of the critical plane-based multiaxial fatigue criterion proposed by Carpinteri et al. [8–12]. In particular, the fatigue

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Nomenclature

a	contact semi-width
c	stick zone semi-width
$\mathbf{C}$	shear stress vector acting on the critical plane
C_a	shear stress amplitude
d_c	critical distance
e	shift of the stick zone induced by the cyclic bulk fatigue stress
E	Young's modulus
E^*	Young's modulus for plain strain condition
F	normal constant loading
H	hot-spot
k	inverse slope of the S-N curve under fully reversed normal stress
k^*	inverse slope of the S-N curve under fully reversed shear stress
L	ElHaddad intrinsic crack length
$\mathbf{N}$	normal stress vector perpendicular to the critical plane
N_0	reference number of cycles
N_a	normal stress amplitude
$N_{f,cal}$	theoretical fatigue life
$N_{f,exp}$	experimental fatigue life
N_m	normal stress mean value
$p(x)$	contact pressure distribution
P	critical point
$q(x)$	shear fretting distribution
$Q(t)$	cyclic shear fretting loading
Q_a	shear fretting loading amplitude
R	radius of the cylindrical fretting pad
$\mathbf{S_w}$	stress vector related to the critical plane orientation
t	time
T_{RMS}	mean square error
$\mathbf{w}$	normal unit vector perpendicular to the critical plane
$W(t)$	weight function
δ	angle between the averaged direction $\hat{1}$ and the normal $\mathbf{w}$ to the critical plane
$\Delta K_{I,th}$	threshold range of the stress intensity factor for long cracks
μ	coefficient of friction within the contact zone
ν	Poisson's ratio
σ_1	maximum principal stress
$\sigma_{af,-1}$	fully reversed normal stress fatigue limit
$\sigma_B(t)$	cyclic bulk fatigue stress
$\sigma_{B,a}$	bulk fatigue stress amplitude
$\sigma_{eq,a}$	equivalent uniaxial stress amplitude
σ_u	ultimate tensile strength
$\sigma_{x,H}$	normal stress at the hot spot
$\tau_{af,-1}$	fully reversed shear stress fatigue limit
ω	pulsation
$\nabla\sigma_x$	gradient of the normal stress around the trailing contact border

assessment is performed by taking into account the stress state related to a material point (named critical point) located at a certain distance from the contact surface. Such a distance is regarded as a material constant, since it is a function of the well-known ElHaddad intrinsic crack length [13].

In order to discuss the influence of the critical point location on the fatigue life estimation, the above distance is here measured along three different paths: a normal path, an inclined path, and a principal stress oriented path. For such three paths used to determine the position of the critical point, the effectiveness of the present criterion is evaluated in terms of fatigue life estimation by comparing the theoretical results with the fretting fatigue data available in Ref. [14]. Such data are related to 2024-T351 aluminium alloy dog bone specimens under cylindrical contacts, being this alloy commonly used in the aerospace industry.

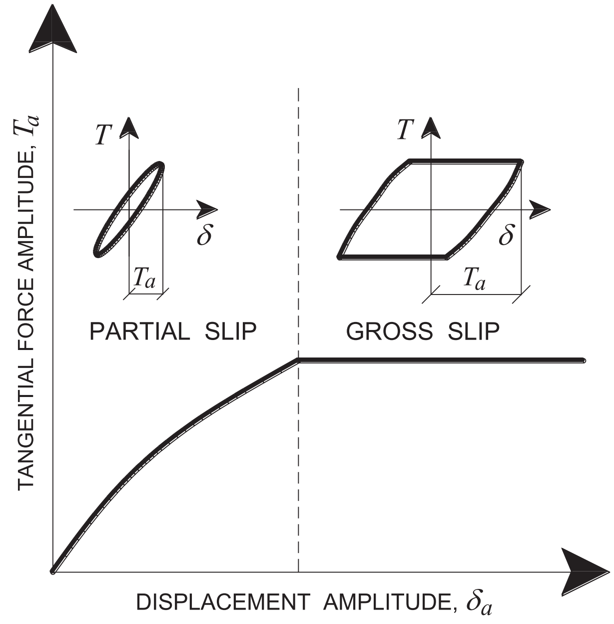

Fig. 1. Fretting sliding conditions: partial and gross slip.

Regarding a distance (to identify the critical point location) only dependent on the material properties, Fouvry and co-workers have recently observed that such a distance tends to overestimate the crack nucleation risk [15]. Consequently, they have argued that not only the material properties but also the severe stress gradients in the contact zone have to be taken into account to correctly determine the critical point position. According to such a remark, a new alternative strategy based on a variable critical distance (function of the stress gradient in the contact zone) is here proposed and experimentally validated.

2. Literature review on fretting fatigue

For years now, both fretting wear and fretting fatigue have been recognised as significant shortcomings in several industrial applications. Whereas fretting wear is associated with long term service operation of mechanical and engineering components including aeroengine couplings [16], locomotive axles [17] and nuclear fuel casings [18], fretting fatigue is associated with short term service operation including bolted and riveted lap joints [19], shrink-fitted shafts [20], metal ropes and cables [21] and dovetail joints of stream and gas turbine blades [22]. An overview of fretting fatigue failures occurred in real structures is presented in Ref. [23].

As has previously been mentioned, a large fraction of life during high-cycle fretting fatigue is spent in crack initiation and, therefore, a crack nucleation approach should be applied to fatigue lifetime evaluation. Such an approach is also needed from a practical point of view because tracking of cracks under fretting fatigue condition is a difficult task, being cracks generally hidden under the contact bodies and so small (generally less than 100 μm) that non-destructive methods are unable to monitor them.

In the above context, multiaxial fatigue criteria are widely used to characterise fretting fatigue behaviour, since bulk fatigue loading causes a multiaxial stress field in the vicinity of the contact