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Methodology to evaluate fatigue damage under multiaxial random loading

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ABSTRACT

Manufacturers must assure the reliability of their products, what implies guaranteeing optimal working conditions during their service life. In this work, a methodology is proposed to estimate the damage experienced by a component under non-proportional loading to be made aiming at predicting when the component will fail and where the failure location will happen. In the present case, a novel cyclic counting model is introduced based on a hybrid variant of the rainflow algorithm applied to the results of the Papadopoulos critical plane approach using the Basquin fatigue model. In this way, the damage model is achieved.

1. Introduction

Industrial components such as bearings, gears, rail-wheels, and cams [1] are usually subjected to thermal treatments in order to achieve a targeted hardness at each layer. For this reason, evaluation of the damage suffered by these components under random loading is a complex task, the solution of which remains nowadays an open issue [2,3]. The application to each particular industrial case presents specific factors that makes it unique [1].

The common feature for this kind of components is that they experience Rolling Contact Fatigue (RCF) in a similar way along their lifetime. Nonetheless, a deeper insight into the particular application case must be made in order to ensure better performance, since each type of component has its own lubrication, third bodies, and geometrical and loading conditions [4].

In all these cases, experimental evidence confirms that the failure originates from the accumulated fatigue at a point in the subsurface that has suffered magnified stresses initiated at the surface. The unforeseen difficulty about this is that there is no simple way to know the magnitude of the stresses in the subsurface [5]. Stresses under the surface arise from the bulk Hertzian stress field, being the shear stress the main reason for the fatigue initiation [6]. Notable differences appear among the above mentioned failure cases impeding a straightforward and unified analysis by applying the results from the classical fatigue point of view, being the differences described next.

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Nomenclature

Latin characters

a	analysed position on the component (m)
b	fatigue strength exponent
c	number of cycles at current stress
i	time step
j	number of element
J	relative distance between loaded element and analysed position (m)
n	unitary vector in normal direction
N	number of cycles for fatigue failure
l, **r**	unitary vector in shear direction
S	traction vector (Pa)
t	Time (s)
Q	load (N)
z	depth (m)

Greek characters

Δ	plane
θ, φ	spherical angle (°)
Ψ	projected curve of shear stresses
σ	stress (Pa)
τ	shear stress (Pa)

Subscripts

$()_a$	amplitude
$()_e$	fatigue limit
$()_{eq}$	equivalent
$()'_f$	strength coefficient
$()_i$	time step
$()_m$	mean
$()_{max}$	maximum
$()_l, ()_n, ()_r$	direction vector
$()_u$	yield strength
$()_x, ()_y, ()_z$	main axes vectors

The state of stress in non-conformal contacts is complex, of multiaxial type and governed by the Hertzian contact theory [7]. While most of classical fatigue cases are analysed as uniaxial fatigue mechanism, RCF is typically a multiaxial fatigue mechanism [8–12], in which the components of the stress tensor history are not proportional to each other in the subsurface [13]. The classical fatigue methodology does not contemplate a hydrostatic stress component, which is present in non-conformal contacts [4,14]. For this reason, a new point of view is required for such cases. Because the principal axes are recurrently changing their direction during a stress cycle, this represents a big handicap to identify the planes where the maximum fatigue damage happens [15,16]. The phenomenon of RCF occurs inside a very small volume of stressed material, because the contact stress field is highly localised [17]. The evolution of the damage caused by the RCF leading to a fatigue splintering involves a three-stage process: shakedown, steady-state elastic response and instability. The plastic deformation at some local points along with the residual stresses are the precursors of the fatigue damage [4,12,13,18,19].

Thus, this research is mainly focused on fatigue models. The main aim of multiaxial fatigue research is to find variables that permit to establish a relation between the results of uniaxial and multiaxial tests. These fatigue tests are necessary in order to characterise the deformation and fatigue behaviour of the material [20]. Several theories have been developed pursuing a solution to this wide range of complex multiaxial fatigue stress situations, which can be classified according to the failure criterion adopted: static yield criteria applied to fatigue, energy-based criteria or critical plane approaches [8,21–23].

The first group, which lastly could be referred to as equivalent stress or strain approaches, has the disadvantage that does not take into account the hydrostatic pressure so that the plastic field of the material cannot be considered [24]. The energy-based criteria include the essential interaction between the elastic and plastic strain fields [8,24]. However, these criteria are