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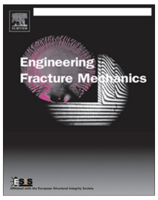

Void coalescence mechanism for combined tension and large amplitude cyclic shearing

K.L. Nielsen [*], R.G. Andersen, V. Tvergaard

Department of Mechanical Engineering, Solid Mechanics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

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ABSTRACT

Void coalescence at severe shear deformation has been studied intensively under monotonic loading conditions, and the sequence of micro-mechanisms that governs failure has been demonstrated to involve collapse, rotation, and elongation of existing voids. Under intense shearing, the voids are flattened, such that the void volume diminishes, whereafter the flattened crack-like voids rotate and elongate until interaction with neighboring micro-voids dominates the material response and coalescence sets in. Eventually, this leads to a complete loss of load carrying capacity. The severe shear loading, imposed at the far boundary, is in an early state of the deformation associated with significant stretching of parts of the void surface, while other parts remain practically un-deformed. A largely uneven distribution of the strain hardening, therefore, evolves along the void circumference and, thus, one cannot expect the void to return to its original shape in the case where the far-field loading is reversed. The present numerical work aims to investigate the evolution of micro-voids subject to constant tension and large amplitude cyclic shearing. The far-field loading, the void shape, and the void growth are monitored, and the calculations are pushed to coalescence and complete loss of load carrying capacity. The initially circular cylindrical voids are predicted to develop protrusions in the shearing plane with normal in the direction of the applied tensile load. These protrusions evolve during repeated cyclic shearing and spread towards neighboring voids - eventually being responsible for void coalescence.

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1. Introduction

Structural failure under conditions, where the number of repeated load cycles is extremely low, is a problem of considerable practical interest. For example, the severe in-plane motion experience during an earthquake can enforce a large amplitude shearing component, which in combination with the existing loads on the structure, gives rise to so-called Ultra-Low-Cycle-Fatigue failure (ULCF failure). Typically, the number of load cycles to failure is $N_f < 100$ (or even below 10). Existing research into the topic is directed by field observations and experimental investigations Iwai et al. [11], Hop- perstad et al. [9,10], Kanvinde and Deierlein [14], Kanvinde et al. [13], Nip et al. [26], Hofmann et al. [8], as well as the development of models to predict when ULCF failure sets in Kuroda [17], Brocks and Steglich [3], Steglich et al. [29], Tateishi et al. [30], Liu et al. [22], Jia and Kuwamura [12], Kiran and Khandelwal [15], Mbiakop et al. [23], Lacroix et al.

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* Corresponding author.
E-mail address: kin@mek.dtu.dk (K.L. Nielsen).

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Nomenclature

A_0	half void spacing in x_1-direction
B_0	half void spacing in x_2-direction
E	Young's modulus
N_f	cycles to failure
n	strain hardening exponent
R_0	initial void radius
T	Stress triaxiality
$\dot{u}_i,\ \dot{u}_{i,j}$	displacement increment and displacement gradient increment, respectively
x_k	Cartesian coordinates
α	scaling factor on tensile component
Δ_0	prescribed shear amplitude
$\dot{\varepsilon}_{ij},\ \dot{\varepsilon}^P_{ij},\ \dot{\varepsilon}^E_{ij}$	total, elastic, and plastic strain increments, respectively
L_{ijkl}	instantaneous moduli
Ω	shearing frequency
Σ_e	far-field effective Mises stress
Σ_{ij}	far-field stress components
Σ_m	far-field mean stress
σ_e	von Mises stress
σ_{ij}	Cauchy stress components
σ_y	initial yield stress
ρ	mass density
v	Poisson ratio

[18]. Compared to monotonic loading, the underlying micro-mechanics that governs ULCF failure has, however, received much less attention.

Focus is here on the case where void growth is responsible for the rapid degradation of the material under cyclic loading and only a few corresponding studies, of the micro-mechanics at play, can be found in the literature. In fact, a void growth to coalescence mechanism under large amplitude cyclic shearing remains to be brought out. The evolution of ductile damage under cyclic loading is termed "ratcheting of the porosity", (referring to a gradual increase in the mean porosity), and is discussed in the early works by Gilles et al. [6], Devaux et al. [5]. The effect essentially reveals itself by a considerably lower strain-to-fracture for a given load level, if it is reached under cyclic conditions rather than monotonically (for fixed stress triaxiality) (see also [16,28]. The well-established micromechanics based Gurson model [7,31] cannot predict this effect, and in an attempt to get a foot on the issue Lacroix et al. [18] recently proposed an improved version of the model by Leblond-Perrin-Devaux (the LPD model, see [20]). In their line of arguments, Lacroix et al. [18] boil it down to the fact that the assumption of positive proportional straining, assumed for the original LPD, cannot be true for cyclic load cases (an assumption originally made to facilitate analytical time-integration of the straining). Instead, Lacroix et al. [18] suggest making use of numerical integration to circumvent this short-coming of the LPD model. Even after several load cycles, their improved model set-up predicts the radial variation in the average strain of the void surface accurately for high-stress triaxiality loading ($T = 3$). However, the prediction is less promising at lower levels of triaxiality as an inconsistency develops close to the free void surface. This inconsistency can well be ascribed the assumption of spherical voids in their model that starts to break down. In nearly parallel studies, Mbiakop et al. [23], Kiran and Khandelwal [15] show that spherical voids grow significantly away from their initial shape at various combinations of Lode parameter and moderate stress triaxiality. In most cases, the void shape remains fairly spherical but develops a ring-band of highly localized plastic flow at the void surface (most clearly visible in Fig. 16 of [23]). This severely deformed ring band region continues to intensify through the repeated cycles and, in the present work, will be demonstrated to give rise to void coalescence.

The objective of the present study is to show results on the void coalescence mechanism that takes place when large amplitude cyclic shearing dominates, rather than focusing on constant triaxiality cyclic loading. The void coalescence under intense monotonic shearing was first brought out in Tvergaard [32,33], and has been shown to distinguish itself significantly from the established void coalescence mechanism at high triaxiality loading, where necking of the intervoid ligaments governs coalescence. Tvergaard [32] showed that, under intense shearing, the micro-voids collapse to form self-contact of the internal void surfaces, whereafter the voids rotate and elongate until interaction with neighboring voids yields coalescence and associated loss of load carrying capacity (see also [34,25,4,24]). However, the questions in focus are now; *how will the severely shear-deformed void evolve if the large amplitude shearing is repeatedly reversed? And, how will its evolution affect the overall material response?*

The paper is structured as follows. The problem of interest is presented in Section 2, while the constitutive model and numerical framework are briefly summarized in Section 3. Results are presented in Section 4 with a focus on the rapid material degradation, the void shape evolution, the void growth, and the void coalescence mechanism. A parametric study and

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