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Prediction of shear-dominated ductile fracture in a butterfly specimen using a model of plastic porous solids including void shape effects

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ABSTRACT

The aim of this paper is to investigate ductile failure under shear-dominated loadings using a model of plastic porous solids incorporating void shape effects. We use the model proposed by (Madou and Leblond, 2012a,b; Madou et al., 2013; Madou and Leblond, 2013) to study the fracture of butterfly specimens subjected to combined tension and shear. This model is able to reproduce, for various loading conditions, the macroscopic softening behavior and the location of cracks observed in experiments performed by Dunand and Mohr (2011a,b). Void shape effects appear to have a very significant influence on ductile damage at low stress triaxiality.

1. Introduction

Ductile fracture is the most common mode of failure of metals and alloys at room and high temperatures. This type of fracture arises from the successive nucleation, growth and coalescence of voids. Although its understanding and modeling have known tremendous progress during the last fifty years (see Benzerga and Leblond (2010) and Pineau et al. (2016) for recent reviews of the topic), many open questions still remain. Among the remaining challenges, the prediction of ductile fracture under conditions of low stress triaxiality (ratio of the mean and von Mises equivalent stresses) has recently been the focus of extensive studies.

From the *experimental* point of view, several recent studies have investigated the initiation of ductile fracture under combined tensile and shear loading (e.g. Mohr and Henn (2007); Barsoum and Faleskog (2007a); Dunand and Mohr (2011a,b); Graham et al. (2012); Haltom et al. (2013); Ghahremaninezhad and Ravi-Chandar (2013); Faleskog and Barsoum (2013); Papasidero et al. (2015)). It is worth noting that all these studies confirm the absence of significant void growth away from the final fracture surface under conditions of dominant shear. It may thus be speculated that macroscopic softening due to important changes of the shape of the voids is responsible for ductile fracture in shear experiments.

From the *numerical* point of view, important efforts have also been dedicated to the study of ductile fracture in finite element micromechanical simulations of elementary porous cells subjected to shear-dominated loadings (Barsoum and Faleskog, 2007b; Leblond and Mottet, 2008; Tvergaard, 2009; Tvergaard and Nielsen, 2010; Scheyvaerts et al., 2011; Nielsen et al., 2012; Tvergaard, 2012, 2015; Dunand and Mohr, 2014). These studies have shown that under conditions of dominant shear, voids rotate, flatten and close up in a mechanism of "mesoscopic strain localization" between voids,[1] leading to macroscopic softening. When the triaxiality increases, a continuous transition is observed between this mechanism and the necking of the ligaments between neighboring voids leading to standard coalescence, as observed numerically in the work of Koplik and Needleman (1988), followed by many others.

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[1] The adjective "mesoscopic" means that localization occurs neither at the microscopic scale nor at the macroscopic scale of the void spacing, but at the intermediate scale of the void diameter.

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From the *theoretical* point of view, a lot of progress has been made on the modeling of ductile fracture since the seminal works of McClintock (1968) and Rice and Tracey (1969), who studied the growth of a single cavity in an infinite plastic matrix and evidenced, for the first time, the essential impact of triaxiality upon the void growth rate. Their work laid the foundations of the modeling of void growth, and was followed by the major contribution of Gurson (1977), who combined homogenization and limit-analysis of a spherical finite cell containing a spherical void to derive a complete and consistent model of plastic porous materials. Due to its intrinsic limitation to spherical voids, Gurson's model cannot predict any softening for a zero triaxiality, because the softening arises in this model only from the increase of the porosity which is nil under such conditions. Several classes of remedies have therefore been proposed in order to account for the softening observed under shear-dominated loadings:

(1) The first class is based on a heuristic modification of the evolution equation of the porosity (Nahshon and Hutchinson, 2008; Xue, 2008). This equation is modified by including an extra term that does not vanish when the triaxiality is zero; this term thus generates some softening in shear. With this modification, the porosity is no longer identical to the true volume fraction of the voids, but can be interpreted as a heuristic damage parameter. Due to its very simple form, the model has been widely used and has notably permitted to successfully reproduce both micromechanical simulations (Tvergaard and Nielsen, 2010) and experiments (Dunand and Mohr, 2011a; Xue et al., 2013) under conditions of dominant shear.

(2) The second class is based on a more micromechanical modeling of void shape effects responsible for macroscopic softening at low triaxiality. Two mathematical frameworks have been developed to derive constitutive models:
   - *Models based on limit-analysis of elementary cells*: Combination of limit-analysis and Hill-Mandel homogenization of some volume element, as first proposed by Gurson himself, permits to effectively operate the scale transition, although it only considers rigid-ideal-plastic materials. In this context, Gologanu et al. (1993, 1994, 1997) extended Gurson's model to spheroidal cavities, using incompressible velocity fields satisfying conditions of homogeneous boundary strain rate on all spheroids confocal with the void.[2] Their model has permitted to reproduce micromechanical simulations involving axisymmetric loadings under conditions of low triaxiality (Gologanu, 1997; Pardoen and Hutchinson, 2000). Recently, a generalization has been proposed in order to account for general ellipsoidal voids (Madou and Leblond, 2012a, 2013,b; Madou et al., 2013), using a family of incompressible velocity fields satisfying conditions of homogenous strain rate on an arbitrary family of confocal ellipsoids, discovered by Leblond and Gologanu (2008). This model has permitted to accurately reproduce micromechanical simulations of Tvergaard and coworkers (Tvergaard, 2009, 2012; Nielsen et al., 2012, 2015) involving shear-dominated loadings (Morin et al., 2016).
   - *Models based on nonlinear homogenization*: Another framework, based on nonlinear homogenization, has been developed to derive constitutive equations of porous materials from rigorous bounds for nonlinear composites (Ponte Castañeda, 1991; Willis, 1991; Michel and Suquet, 1992). The models derived using the so-called “variational” approach (Ponte Castañeda and Zaidman, 1994; Kailasam and Ponte Castañeda, 1998) naturally account for void shape effects but severely overestimate the limit-load for predominantly hydrostatic loadings. Later, Danas and Ponte Castañeda (2009) developed a model based on more refined bounds that has been applied to structures subjected to shear-dominated loadings (Danas and Aravas, 2012).

The aim of this paper is to investigate ductile failure under shear-dominated loadings, using a micromechanical model of plastic porous solids incorporating void shape effects. The model selected is that developed by (Madou and Leblond, 2012a, 2013,b; Madou et al., 2013). This model is applied to the numerical simulation of Dunand and Mohr (2011a,b)'s experiments of ductile failure of “butterfly” specimens subjected to combined tension and shear.

The paper is organized as follows:

- Section 2 briefly presents Dunand and Mohr (2011a,b)'s experiments.
- Section 3 recapitulates the Madou-Leblond model. The primitive form of the model (Madou and Leblond, 2012a, 2013,b; Madou et al., 2013) is completed with heuristic extensions so as to include coalescence of voids and strain hardening, following Morin et al. (2016).
- In Section 4 we investigate the predictions of the Madou-Leblond model, as applied to the experiments presented in Section 2. The force-displacement curves and the location of the cracks are notably investigated.

2. Experimental procedures

We recall in this section the basic setup of the experiments performed by Dunand and Mohr (2011b, a) that we will try to reproduce with an advanced model of ductile fracture.

2.1. Bi-axial experiments

The bi-axial fracture experiments are performed with a dual actuator system (see Fig. 1a) that permits to apply a combination of normal and transverse loads on the edge of a “butterfly specimen”. The specimen, represented in Fig. 1b, includes a gage section of reduced thickness that has been designed in such a way that fracture is prone to initiate at its center. The ratio of the vertical force F_V and the horizontal force F_H applied is characterized by the bi-axial loading angle β defined by

$$\tan\beta = \frac{F_V}{F_H}, \tag{1}$$

where $\beta = 0^\circ$ corresponds to pure shear and $\beta = 90^\circ$ to tension. Four different loading conditions are investigated: $\beta = 0^\circ$ (pure shear), $\beta = 25^\circ$ (shear-dominated loading), $\beta = 63^\circ$ (tension-dominated loading) and $\beta = 90^\circ$ (tension). The experiments are performed under force control to enforce the desired value of the loading angle β.

2.2. Material

The experiments are performed on a TRIP780 steel. This material features a complex multiphase microstructure composed of

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[2] In a variant, Garajeu et al. (2000) considered a velocity field orthogonal to all such spheroids.