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Characterization of the nonlinear behavior of nodular graphite cast iron via inverse identification—Analysis of uniaxial tests

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A B S T R A C T

The aim of this work is to estimate the parameters of elastoplastic and damage laws for nodular graphite cast iron from a cyclic uniaxial test on a dog-bone sample. The paper focuses on the identification of material parameters coupling finite element models and full-field measurements. The gap between the measured and simulated data is used to estimate the quality of the proposed constitutive postulates.

Last, a cyclic uniaxial experiment is carried out in a lab tomograph to reveal the damage micro-mechanism. Digital volume correlation is used to measure displacement fields in the bulk of the sample. The correlation residuals are used to detect the damage mechanism occurring in the heterogeneous microstructure of the material.

1. Introduction

The way of identifying material parameters to describe constitutive postulates has experienced major changes with the development of full-field measurement techniques (*e.g.*, Digital Image Correlation (DIC), moiré and speckle interferometry, and grid methods (Grédiac and Hild, 2012)). Different approaches (Avril et al., 2008a) are developed to obtain the sought parameters with various measured data (*i.e.*, displacement or strain fields, load levels). These identification methods are applied to model different phenomena (*e.g.*, elasticity (Avril et al., 2008a; Gras et al., 2015), plasticity (Grédiac and Pierron, 2006; Cooreman et al., 2007; Robert et al., 2012; Réthore et al., 2013; Mathieu et al., 2015), damage (Claire et al., 2002; Chalal et al., 2004; Réthoré, 2010; Wu et al., 2011; Bouterf et al., 2015)) from a wide range of experiments.

In a review on the identification of elastic properties (Avril et al., 2008a) five different identification methods were introduced. In general the material parameters can be obtained by iteratively updating or direct identification procedures. The following iterative methods *Finite Element Model Updating* (FEMU), *Constitutive Equation Gap Method* (CEGM), *Reciprocity Gap Method* (RGM) use computed displacement and/or stress fields by FE analyses. An FE computation with an initial guess of the constitutive parameters is needed, while material parameters are identified by minimizing a cost function where the available measurements are compared with their computed counterparts. The cost functions for FEMU-U (*displacement method*), FEMU-F (*force method*) and FEMU-UF (*displacement & force method*) are usually defined as quadratic errors of measured and computed values.

Contrary to updating procedures, non iterative methods such as the *Virtual Fields Method* (VFM) (Grédiac, 1989) and *Equilibrium Gap Method* (EGM) (Claire et al., 2002) use measured strain/displacement fields to determine material parameters (Avril et al., 2008a). In comparison with updating techniques a big advantage of these methods is the smaller duration of computation since they do not require a series of FE calculations.

Very few identifications have been conducted to account for elastoplasticity and damage. However, both phenomena were investigated separately with non-iterative (*i.e.*, EGM (Claire et al., 2004, 2007)), and iterative identification methods, namely, FEMU (Cooreman et al., 2007; Robert et al., 2012; Mathieu et al., 2015), VFM (Avril et al., 2008b; Pierron et al., 2010), CEGM (Latourte et al., 2008). Damage identification from full-field measurements was first proposed by resorting to the equilibrium gap method (Claire et al., 2004). It consists of a finite element formulation in which the nodal displacements are known and the elastic properties (*i.e.*, the damage field) are sought. Elastic properties are assumed to

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remain uniform over each element, but vary from element to element. The damage field is nothing but a simple way to account for a heterogeneous stiffness within the sample. The additional step that has been tested against experimental data is to require for constitutive consistency, namely, that the damage inhomogeneity results from a homogeneous damage law combined with a heterogeneous loading (Roux and Hild, 2008). EGM has the advantage of being directly applicable as a post-processor to the current displacement field measurement techniques such as digital image correlation.

Rossi et al. (2006) identified damage parameters of Lemaitre's model from a uniaxial experiment. The main aim was to show how digital image processing may be used in material testing and characterization. DIC was used to obtain the plastic strain from which five parameters were obtained. Pierron et al. (2010) made an extension of the virtual fields method to combine isotropic and kinematic hardening. Displacements were obtained by using the grid method. Since stress-related parameters were identified load measurements were included in the identification procedure. Based on the effect of noisy data to the cost function the choice of optimal virtual fields was investigated.

CEG-based methods (Latourte et al., 2008) have also been proposed and applied in the context of nonlinear constitutive models. The identification of heterogeneous elastoplastic properties (*i.e.*, linear kinematic hardening) and strain energy densities from kinematic field measurements have been addressed. The identification was based on an incremental version of CEGM where tangent or secant stiffness operators associated with elastoplastic models are sought.

Integrated DIC (or I-DIC) was also considered to tune elastoplastic (Réthore et al., 2013; Mathieu et al., 2015) and damage models (Réthoré, 2010) *independently*. Initially such types of techniques used closed-form (*i.e.*, elastic) solutions (Hild and Roux, 2006; Roux and Hild, 2006). They were subsequently generalized by numerically generating sensitivity fields to material parameters for linear or nonlinear constitutive laws (Leclerc et al., 2009; Réthoré, 2010; Mathieu et al., 2015). Very recently, it was shown that when properly weighted, FEMU and I-DIC lead to similar parameter uncertainties in the limit of small measurement uncertainties (Mathieu et al., 2015).

In the present paper weighted FEMU coupled with global DIC (Besnard et al., 2006) will be used to tune elastoplastic material properties from a quasi-static uniaxial experiment. The proposed method was already applied for the identification of elastoplastic material parameters (Cooreman et al., 2007; Robert et al., 2012; Mathieu et al., 2015). However, the cost functions were not weighted by covariance matrices associated with measurement uncertainties, which probe the level of each considered quantity with respect to its uncertainty level and accounts for correlations when needed. Three different constitutive postulates will be used herein to describe the nonlinear behavior (*i.e.*, isotropic hardening, kinematic hardening and isotropic hardening coupled with damage). The main goal of the present paper is to determine the elastoplastic behavior coupled with damage by analyzing loading and unloading steps in one identification procedure. Second, the results obtained with different material models will be compared in terms of displacement and force residuals in order to provide the most reliable constitutive model among the proposed laws. Last, in order to detect damage micromechanisms an in-situ cyclic uniaxial test was performed in an X-ray tomograph. Regularized Digital Volume Correlation (RC8-DVC (Taillandier-Thomas et al., 2014)) measures displacement fields in the observed volume. The correlation residuals will be used to detect damage.

2. Mechanical test and material

The material considered in this study is spheroidal graphite (SG) cast iron. At the macroscopic level SG cast iron is considered to be homogeneous with isotropic elastic properties although it is heterogeneous at a microscopic level. The heterogeneous microstructures of ductile cast iron consist of a ferritic matrix containing randomly distributed graphite inclusions (Fig. 1).

A cyclic tensile test was carried out with an electro-mechanical testing machine on a dog-bone sample. The region of interest is approximately 50-mm long, its ligament is 10-mm wide, and the sample is 5-mm thick. The measurement protocol used herein consisted of an optical setup (for DIC measurements) on one side of the sample while for validation purposes a strain gauge was mounted on the other side. Before the experiment, the specimen was prepared for DIC purposes. An artificial texture (*i.e.*, speckle pattern) was applied with white and black paints sprayed over the ligament. The latter was observed with a single camera (*i.e.*, 2D-DIC measurements). A telecentric lens with a magnification $\times 4$ was mounted on a *PCOedge* camera (16-bit digitization, definition: 2560 $\times$2160 pixels). The chosen lens allows artifacts related to out-of-plane motions to be minimized (if not completely canceled out). The physical size of one pixel on the acquired images corresponds to 52 μm. The strain gauge data were compared with DIC measurements to validate the latter ones with the present optical setup. A very good consistency was observed (Tomičević, 2015).

Figure 2 shows the cyclic loading path. The experiment was conducted in a displacement controlled mode with a loading rate of 3 μm/s except for the first cycle (0.5 μm/s). The first two cycles with maximum loads 8 and 12 kN were performed in the elastic regime.

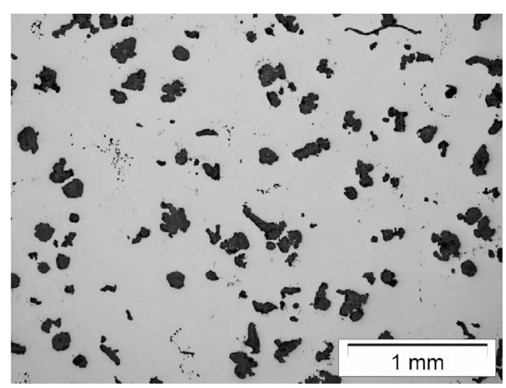

Fig. 1. Metallography of the investigated SG cast iron.

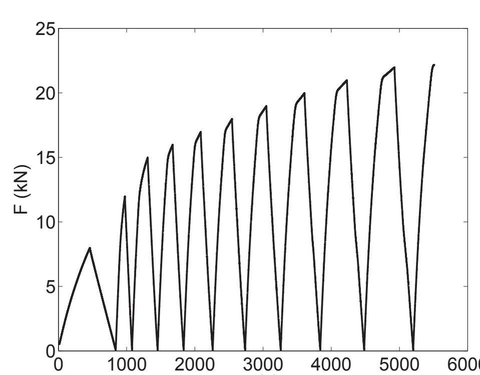

Fig. 2. Loading history for the uniaxial cyclic experiment. The image acquisition rate was 1 frame/s.