Optics and Lasers in Engineering 53 (2014) 142–151

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Characterisation of steel components under monotonic loading by means of image-based methods

J. Xavier [a,*], J.C.R. Pereira [b], A.M.P. de Jesus [b,c]

[a] CITAB, University of Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal
[b] IDMEC-FEUP, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] SCT, University of Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal

ARTICLE INFO

Article history:
Received 8 June 2013
Received in revised form
3 September 2013
Accepted 4 September 2013
Available online 27 September 2013

Keywords:
Digital image correlation
Feature-tracking method
Non-linear finite element modelling
Mechanical testing
Ductile damage behaviour

ABSTRACT

Ductile damage behaviour of S185 structural steel is determined by coupling numerical and experimental analyses. Monotonic experimental tests are carried out in five different specimen configurations. These mechanical tests are coupled with image-based methods for assessing displacement and strain fields over the gauge section. Three different ductile damage models proposed in the literature for monotonic loading are analysed. Their governing parameters are determined by comparing experimental and numerical mechanical responses. Measurements provided by digital image correlation and feature-tracking methods are used for calibrating and validating non-linear finite element modelling. Numerical analyses built in ANSYS are carried out to compute the necessary parameters (stress–strain and triaxiality histories) to calibrate Johnson–Cook (JC) and Kanvinde–Deierlein (KD) fracture criteria. Also, a calibration of the Gurson–Tvergaard–Needleman (GTN) model is performed based on an explicit finite element analysis in ABAQUS.

1. Introduction

Monotonic ductile fracture on steel components can occur due to extreme loading conditions such as support settlements, hurricanes, earthquakes, industrial plant shutdown and accidental loads. Several models have been already proposed for ductile or plastic monotonic fracture such as empirical models, void growth models, porosity-type models and continuum damage mechanics based models [1]. Empirical models relates the equivalent plastic strain at fracture with a suitable triaxiality function. Examples of such formulations are the propositions by Cockcroft–Latham [2], Datsko–Yang [3], Brozzo [4], Norris [5] and Johnson–Cook [6]. Void growth micromechanical models have a similar formulation as empirical models. However, these models are based on voids evolution at the microscale, as referred by McClintock [7], Rice-Tracy [8] and Kanvinde–Deierlein [9]. For empirical and void micromechanical models, damage and plasticity are completely decoupled [1]. The porosity-based models have been proposed after Gurson [10] and Tvergaard-Needleman [11,12]. These models assume that the ductile fracture in metal components is caused by nucleation, growth and coalescence of microvoids presented inside the material microstructure. This model considers the size of the plastic yield surface dependent on the fraction of porosity in the material, which in turn depends not only on second invariant of the stress tensor, but also on pressure. Originally introduced by Lemaitre [13], the CDM models are based on a consistent thermo-dynamic framework, where damage is estimated by the loss of stiffness in the material. Bonora [14] proposed later a non-linear law for damage evolution instead of the originally linear one proposed by Lemaitre [13]. Some of these damage models (empirical and void growth models) are usually uncoupled from plasticity and are applied to post process stress–strain history data from non-linear plastic analysis. Therefore, they are suitable to model crack initiation. Porosity-type and continuum damage mechanics based models are typically coupled models, and can be used to model both damage initiation and damage evolution until the final failure of the component. The general trend of the ductile damage models is to consider a dependency on the stress triaxiality. More recently, Wierzbicki et al. [15] have demonstrated a dependency of the ductile fracture also on the third invariant of the stress tensor. Nevertheless, this study will not cover variations in the third invariant of the stress tensor.

The identification of the parameters governing the damage models requires a hybrid experimental–numerical approach, because, in general, the parameters cannot be determined directly from measurements. The experimental techniques are important to generate global as well as local information to calibrate the numerical models. Therefore, full-field optical techniques are attractive to this purpose. Moreover, concerning the measurements of large plastic deformations, non-contact optical methods

* Corresponding author. Tel.: +351 962761277.
E-mail address: jmcx@utad.pt (J. Xavier).

0143-8166/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.optlaseng.2013.09.004

are advantageous over point-wise contact counterpart techniques such as strain gauges and extensometers due to their physical limitations. Full-field optical methods of displacement and strain measurements have been increasingly used in experimental solid mechanics [16]. These techniques can be generically sorted, according to the physical phenomenon involved in the measurements, such as white-light (*e.g.*, moiré or grid methods and digital image correlation) and interferometric (*e.g.*, speckle and moiré interferometry) methods. The choice of a given technique can be driven by several criteria such as the cost, the set-up apparatus (simplicity, flexibility, sensitivity to vibrations, etc.), the performances (resolution, spatial resolution, etc.), the measuring quantity (displacement, strain, etc.), and the length scale of observation (from structural down to micro or nano). In contrast to punctual techniques these methods provide full-field data and are contact-free. This type of experimental data has allowed new insights into different engineering problems, such as non-destructive testing, validation of constitutive models or multi-parameter identification from single test configurations [17].

Among these techniques, non-interferometric methods based on the image and signal processing have been increasingly used, such as digital image correlation (DIC) [18–24], feature-tracking method (FTM) [25–28] and grid method (GM) [29,30]. This sort of techniques differs in terms of post-processing, but they share the same underlying principle of assessing the deformation of an object by analysing the geometrical deformation of a suitable pattern, which is assumed perfectly attached to the material surface substrate. In DIC, the target surface has typically a random textured (speckled) pattern, which either exists naturally or can be created, for instance, by painting. In GM, a carrier grid consisting of crossed vertical and horizontal lines of a given pitch is transferred (glued) to the surface of interest. Both DIC and GM provided full-field displacements of a (quasi-)planar object and have been applied to a variety of mechanical and fracture problems, taking advantage of good balance between spatial resolution and resolution. However, there are certain case studies where neither a random nor a periodic pattern can be conveniently applied to the surface of interest. In such cases, the FTM can eventually be a suitable method since it only requires few marks (*i.e.*, local features with a suitable colour, shape and size) over the region of interest, which can be easily transferred to a background surface using ink or tape adhesive. Normally, this technique does not have the same spatial resolution than counterpart DIC and GM techniques, but can be suitable for measuring strains over uniform or moderate gradient fields [25,31].

In this work, constitutive material parameters describing the ductile damage behaviour of S185 structural steel were investigated by coupling numerical and experimental analyses. Models proposed by Gurson–Tvergaard–Needleman (GTN) [10,12], Johnson–Cook (JC) [6] and Kanvinde–Deierlein (KD) [9] were used for modelling ductile damage under monotonic loading. The constitutive parameters of these models are to be determined from suitable experimental methods. Tensile tests were proposed using planar and cylindrical specimens with different configurations. Under monotonic tensile loading, these specimens exhibit a constant deviatoric stress parameter equal to unity [15]. Therefore, JC and KD models are suitable choices since they only depend on stress triaxiality. Mechanical tests on planar specimens were coupled with DIC, whilst the cylindrical specimens were analysed based on FTM. The feature tracking was performed using an algorithm based on the centroid detection of target objects. Full-field measurements together with load–displacement curves along relevant paths across the gauge section were used to calibrate a plasticity model with isotropic hardening, which is included in finite element models of the investigated geometries. Numerical analyses were conducted to compute the necessary parameters (stress–strain and triaxiality histories) to calibrate JC and KD ductile fracture criteria. The calibration of the GTN model was based on an explicit finite element analysis.

2. Experimental work

2.1. Materials and test methods

In order to identify the material parameters figuring in the models for monotonic ductile fracture proposed in this work (Section 3.1), tensile tests were performed in five different configurations (Fig. 1): (i) dog bone (DB), (ii) plate with circular hole (PCH), (iii) smooth cylindrical (SC); (iii) large notch cylindrical (LNC); and (v) small notch cylindrical (SNC). These specimens were cut from a S185 structural steel plate with 8 mm thickness. The monotonic tensile tests were carried out in a servo hydraulic Instron 8801 testing machine at room temperature under an actuator velocity of 1 mm/min. Load was measured by means of a load cell of 100 kN.

2.2. Integrated image-based methods

2.2.1. Digital image correlation

DIC provides full-field displacements of a target object by comparing the similarity of speckled features, characterising the material surface, in images acquired at distinct mechanical configurations. In a local approach, the reference image (undeformed configuration) is typically meshed into correlation domains of $(2M+1)\times(2N+1)$ pixels/subset, where M and N are the number of pixels in the x and y image directions, respectively. It is assumed that the pixel grey distribution within each subset defines a unique and local fingerprint of the surface with suitable contrast and isotropy. The size of the subsets must be carefully defined in a compromise between correlations and interpolation errors, since an independent value of the displacement is measured per subset, defining the spatial resolution of the method. A sub-pixel correlation algorithm must then be used to compute the position (centre) of each subset on the deformed configuration. The DIC method can be used in two complementary configurations for measuring 2D and 3D displacements [20,32]. DIC-2D measures the in-plane displacements of a (quasi-)planar surface of interest and it requires the utilisation of only one digital camera. On the other hand, the DIC-3D (stereovision set-up) provides both in-plane and out-of-plane displacements (although with different resolutions). Conventionally, two identical optical systems (*i.e.*, digital camera, lenses, aperture, focal length, etc.) are used. The stereovision system has the advantage of taking into account (at least at a certain extent) both parasitic out-of-plane movements and contraction effect (*Poisson*'s effect) that can occur during experimental tests. Moreover, it can be more properly applied to specimens with moderate curved surfaces. However, it requires a calibration procedure of the stereovision system for evaluating the camera model parameters, which can be time consuming.

Several mathematical correlation criteria have been proposed for estimation of the displacement fields in the subset matching process. It has been shown that the zero-normalised sum of squared differences (ZNSSD) is a robust algorithm since it takes into account both offset and linear scale variations of light intensity and is most efficient when using an iterative procedure for the minimisation problem [19]. The correlation process has to be solved for a set of deformation parameters which will characterise the mapping function (shape function). Iterative algorithms can then be used for finding the optimal deformation parameters optimising the correlation coefficient [19,33].

DIC measures displacements across a whole region of interest. However, strain fields are usually needed in solid mechanics.