C. R. Mecanique ••• (••••) •••–•••

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Computational modeling of material forming processes / Simulation numérique des procédés de mise en forme

On the identification of a high-resolution multi-linear post-necking strain hardening model

Kristof Denys, Sam Coppieters, Dimitri Debruyne *

Department of Materials Engineering, KU Leuven, Campus Ghent, Gebroeders De Smetstraat 1, B-9000 Gent, Belgium

A R T I C L E   I N F O

Article history:
Received 7 April 2017
Accepted 27 July 2017
Available online xxxx

Keywords:
FEMU
Post-necking
Strain hardening
Stereo-DIC
S690QL

A B S T R A C T

The Finite Element Model Updating (FEMU) technique is an inverse method that enables to arrive at a complete solution to the problem of diffuse necking of a thick tensile specimen. Conventionally, FEMU relies on the identification of a phenomenological strain hardening law that inherently limits the accuracy of the method due to the predefined character of the adopted strain hardening law. A high-resolution multi-linear post-necking strain hardening model enables to describe more generically the actual strain hardening behaviour. A numerical concept study is used to scrutinise the identification of such a model using FEMU. It is shown that, unlike progressive identification strategies, a global identification strategy followed by a smoothing operation based on area conservation yields sufficiently accurate results. To study the experimental feasibility, the latter strategy is used to identify the post-necking strain hardening behaviour of a thick S690QL high-strength steel. To this purpose, a notched tensile specimen was loaded up to fracture, while the elongation was measured using Digital Image Correlation (DIC). It is shown that the global identification strategy suffers from experimental noise associated with DIC and the load signal.

1. Introduction

In recent years, fracture mechanics is gaining more interest from industry. For example, the line pipe industry aims at an accurate estimation of the amount of deformation high-strength steel can undergo before failure occurs [1–3]. Also the automotive industry is interested in studying the ductile fracture behaviour of advanced high-strength metals [4] during forming [5] and joining [6]. Finite Element modelling strategies are used to predict and understand ductile fracture phenomena. It is well known that this requires the knowledge of the strain hardening behaviour beyond the onset of necking.

To obtain the flow curve beyond the onset of necking, the strain hardening behaviour in the pre-necking region obtained using the conventional method can be extrapolated. However, no guidelines are available to correctly extrapolate the pre-necking stress–strain curve. Some attempts consist in extrapolating the found phenomenological model, which approximates best the pre-necking strain hardening behaviour [7]. Extrapolation, however, is disputable because the post-necking yield curves are obtained without any information from the targeted deformation phase. Hence, this procedure can lead to different and potentially very unsafe results [8,9].

* Corresponding author.
E-mail addresses: kristof.denys@kuleuven.be (K. Denys), Dimitri.debruyne@kuleuven.be (D. Debruyne).

https://doi.org/10.1016/j.crme.2018.06.002

To tackle this problem, several authors have used inverse methods such as Finite Element Model Updating (FEMU) to characterise the stress–strain curve beyond the point of maximum uniform elongation [7,10–12]. The FEMU approach identifies a phenomenological strain hardening law which limits the procedure to fit a prescribed analytical function to the actual strain hardening behaviour of the material. Consequently, FEMU merely yields a best fit resulting in unavoidable errors due to the material's actual strain hardening behaviour. A more flexible strain hardening law can be obtained by a combination of analytical functions [9,13,14]. Even though these combined functions could potentially result in a better approximation of the strain hardening behaviour, a predefined analytical function is still fitted. Moreover, the user is always confronted with the difficult choice between different functions to obtain the best fit for the material under investigation.

To solve the inflexibility of phenomenological strain hardening laws to accurately describe the full plastic strain range, the possibility of characterising a generic analytical function has been investigated in this paper. Because FEMU will be used, the function should consist out of a minimum number of parameters to limit the computational cost. Therefore, the easiest method is to characterise a piecewise linear function, also referred to as a multi-linear function. Kajberg et al. [11] identified a multi-linear function composed out of four linear functions over a plastic equivalent strain ($\epsilon_{\text{pl}}^{\text{eq}}$) range of 0.8. Because a linear function is fitted over a large strain interval, the accuracy of such an approximation is disputable for a wide range of metals. Furthermore, a constraint was applied to limit the strain hardening behaviour to a monotonously positive decreasing slope, which additionally limits the flexibility. Koc et al. [7] progressively identified a multi-linear function. The latter procedure starts with the identification of one linear function, followed by one-by-one addition of other linear functions. However, only two linear functions are identified over an $\epsilon_{\text{pl}}^{\text{eq}}$ interval of 0.66, whereof the accuracy is again questionable.

In this paper, the inverse identification of a high-resolution multi-linear post-necking strain hardening model is investigated. First, different identification strategies are evaluated using a numerical concept study. Finally, the experimental feasibility of the proposed identification strategy is studied by identifying the post-necking strain hardening behaviour of a 10-mm-thick S690QL High Strength Steel (HSS).

2. Methodology and numerical concept study

2.1. Inverse procedure

FEMU has been widely applied to identify the elastoplastic material properties of sheet metal using phenomenological strain hardening laws [11,15–17]. The basic idea of this procedure is to minimise the discrepancy between experimentally measured and numerically computed surface strains while adapting the material parameters. The surface strains are often measured using Digital Image Correlation (DIC) [18].

In this work, the aim is to extract the strain hardening behaviour from the diffuse neck during a tensile test using FEMU. Comparing the experimentally measured and numerically computed surface strain fields over the entire surface of the specimen would result in redundant information because only the strain fields over the necking region will change during a tensile test in the post-necking area. Moreover, comparing both strain fields at exactly the same location is a difficult problem to cope with [15]. The latter issue can be solved by using a notched tensile test coupon as shown in Fig. 1. The deformation will localise in the vicinity of the red dashed lines shown in Fig. 1. As such, instead of using full-field surface data, the average displacement in the X-direction has been extracted on the red dashed lines. The Y position of the extraction lines has been chosen close to the local necking zone to have more sensitivity to the post-necking parameters, resulting in a more accurate identified strain hardening behaviour. In this work, the extraction lines are at 1 mm above and below the centre of the specimen. The local engineering strain e is calculated as:

$$e = \frac{ext_{\text{u}} - ext_{\text{l}}}{L_0} \tag{1}$$

with ext_{u} and ext_{l} being the averaged displacements at the upper and lower extraction lines, respectively, and L_0 the original length between the two extraction lines (represented as the red dashed lines in Fig. 1). The local engineering strain e is merely defined here to have a local measure that can be used in the cost function. Indeed, the difference between the measured and numerically computed local engineering strain, e^{exp} and e^{num} respectively, is used in the following cost function to minimise:

$$C(\mathbf{p})_e = \sum_{i=1}^{m} \left(e^{\text{exp}} - e^{\text{num}}\right)^2 \tag{2}$$

with m the number of load steps and $\mathbf{p}$ the parameter vector containing the unknown parameters in the strain-hardening model. In case of a multi-linear strain hardening model, the unknown parameters are the slopes of the linear functions. The length of the vector $\mathbf{p}$ depends on the resolution of the model, i.e. the interval in terms of plastic equivalent strain spanned by a single linear function.

Identifying the post-necking strain hardening behaviour requires a displacement-driven FE simulation to exclude plastic instability problems. Consequently, not only the local strain e can be minimised in the FEMU procedure, but also the force