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Identification of strain hardening phenomena in sheet metal at large plastic strains

Sam Coppieters[a,]*, Kazuhiro Ichikawa[b], Toshihiko Kuwabara[b]

[a]*Department of Materials Engineering, KU Leuven, Campus Gent, Gebroeders De Smetstraat 1, 9000 Gent, Belgium*
[b]*Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, 2-24-16, Nakacho, Koganei-shi, Tokyo, 184-8588, Japan*

Abstract

A new experimental/numerical method to identify post-necking strain hardening phenomena in ductile sheet metal is presented. The identification of the post-necking strain hardening behaviour is based on the minimization of the external and the internal work in the necking zone during a tensile test. The proposed method takes the material state and the shape of the whole deforming tensile specimen into account. The post-necking hardening behaviour of a cold rolled interstitial-free steel sheet is identified. A hardening law which enables disentangling pre –and post-necking strain hardening behaviour is presented. The method is experimentally validated using an independent material test. For that purpose, the uniaxial tube expansion test is conducted to obtain uniaxial strain hardening behaviour beyond the point of maximum uniform strain in a tensile test. Finally, the presented method is compared with a hydraulic bulge test.

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Keywords: Post-necking strain hardening; Sheet metal; Diffuse neck, Work hardening; Large plastic strains

* Corresponding author. Tel.: +32-9-265-86-10; fax: +32-9-265-86-48.
E-mail address: sam.coppieters@kuleuven.be

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1. Introduction

Many sheet forming processes generate plastic strains well beyond the point of maximum uniform strain (e.g. deep drawing and clinch forming). The most common way to determine the stress-strain relation is by conducting a standard tensile test. If standard equipment and analytical formulas are used, those tests only allow the identification of the hardening behaviour up to the point of maximum uniform elongation. The problem of diffuse necking has been tackled in the past using different levels of approximation. Several researchers have arrived at the so-called complete solution of the general problem of diffuse necking envisioned by Bridgman (1952). A complete solution takes the material state and the shape of the whole deforming specimen into account. The majority of the studies dealing with the complete solution is based on the finite element-based inverse approach, e.g. Kajberg and Lindkvist (2004). Although the finite element-based method enables successful identification of post-necking phenomena, there are a number of shortcomings associated with this technique. From an experimental point of view it can be burden to perfectly couple the experimentally measured quantities and the numerically computed response (e.g. the strain field). In addition, it is still an arduous task to build a reliable finite element model capable of dealing with the plastic instability. Moreover, these calculations are very time-consuming. In order to avoid these shortcomings, alternative identification strategies based on the complete solution have been developed by Coppieters et al. (2011) and Kim et al. (2013). Such methods can be easily validated in the pre-necking regime. Independent experimental validation of such methods in the post-necking regime, however, is much more challenging. Indeed, from an experimental point of view it is very difficult to probe large plastic strains under uniaxial tension due to plastic instabilities. The main focus in this paper is on the independent experimental validation of the method presented by Coppieters et al. (2011). For that purpose, the multiaxial tube expansion test machine developed by Kuwabara and Sugawara (2013) is used to probe uniaxial strain hardening behaviour beyond the point of maximum uniform strain in a tensile test. The latter test is referred to as the uniaxial tube expansion test. In this paper we scrutinize the accuracy of the identification method presented by Coppieters et al. (2011) by comparing the results with the uniaxial tube expansion test. The next section briefly introduces the method of Coppieters et al. (2011), in the remainder of this work referred to as the post-necking tensile experiment. Additionally, an alternative hardening law which enables disentangling pre –and post-necking hardening behaviour is presented. Next, the post-necking tensile experiment is experimentally validated using the uniaxial tube expansion test. In section 4, the result of the post-necking tensile experiment is compared with the hydraulic bulge test. Finally, conclusions are drawn in the last section.

Nomenclature

W_{int}	Internal work
W_{ext}	External work
p	Unknown set of hardening parameters
F	Tensile force
u_i	Displacement component in the X-direction of element node i
v_i	Displacement component in the Y-direction of element node i
u	Elongation of the region in which the diffuse neck develops

2. Post-necking tensile experiment

The method presented by Coppieters et al. (2011) was originally conceived from the observation that in a quasi-static tensile test the internal work equals the external work. The key point of the method is the minimization of the discrepancy between the internal work W_{int} and the external work W_{ext} in the necking zone during a tensile test. Fig. 1 depicts a homogenous tensile specimen which develops a diffuse neck in the dark shaded region beyond the point of maximum load. Assume that we can calculate the internal work W_{int} and the external work W_{ext} in the region spanned by A-B-C-D. The primary aim is then to identify the unknown hardening behaviour by iteratively minimizing the discrepancy between the internal work W_{int} and the external work W_{ext}. For this purpose, a least squares cost function can be constructed:

$$C(\boldsymbol{p}) = \frac{1}{2}\sum_{j=1}^{l}\left[(W_{\text{int}}(\boldsymbol{p}))_j - (W_{ext})_j\right]^2, \tag{1}$$

where l is the number of measurements and $\boldsymbol{p}$ is the set of unknown hardening parameters. The computation of the internal work W_{int} and the external work W_{ext} is based on the following assumptions:

- The lines A-B and C-D (see Fig. 1) remain straight during the tensile test.
- The volume of the specimen is constant.
- Plane stress conditions prevail in the specimen.

The external work W_{ext} can be easily computed using the tensile force F and the elongation (measured by any suitable method) of the dark shaded region in Fig. 1. The computation of the internal work W_{int}, however, is more complicated and requires access to the strain field and the stress field. In this work, the experimental displacement field is measured using digital image correlation. Next, an element mesh (see Fig. 1) is fitted to the available experimental data which yields displacements (u_i, v_i) in each node i of the element mesh. The latter enables computing the strains in each element of the mesh. The stress field associated with the experimentally measured strain field is obtained with the aid of a return mapping algorithm, also referred to as a stress update algorithm. Such algorithms use the concept of a yield function and a hardening law. In this work, the Yld2000-2d yield function developed by Barlat et al. (2003) was adopted. The parameters of this yield function for the material used in this study were identified in advance by Ichikawa et al. (2014) and can be found in Table 1. A hardening law which enables to disentangle pre –and post-necking hardening was used this study:

$$\sigma_{eq} = \begin{cases} K(\varepsilon_0 + \varepsilon_{eq}^{pl})^n & \textbf{\textit{if}}\ \varepsilon_{eq}^{pl} \le \varepsilon_{\max} \\ K(\varepsilon_0 + \varepsilon_{\max})^n + Q[1 - e^{-p(\varepsilon_{eq}^{pl} - \varepsilon_{\max})}] & \textbf{\textit{if}}\ \varepsilon_{eq}^{pl} > \varepsilon_{\max} \end{cases}. \tag{2}$$

where the parameters K, ε_0 and n are readily available from the pre-necking data. When the plastic equivalent strain ε_{eq}^{pl} becomes larger than the maximum uniform strain ε_{max}, the model switches to a post-necking hardening description. In order to have a smooth transition between pre –and post-necking hardening a relation can be found between Q and p. As such, the only unknown in Eq. (2) is the post-necking parameter p which guarantees a fast identification. More importantly, Eq. (2) enables to describe a variety of post-necking hardening behaviours whilst retaining the accuracy in the pre-necking regime. If p is small, Swift-type hardening is retrieved. Voce-type hardening can be described by a large value of p. This model is referred to as the p-model in the remainder of this work.

Table 1. Parameters of the Yld2000-2d yield (reference plastic strain ε_0=0.289)

α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_8	M
0.6339	1.3875	1.0885	0.8865	0.9419	0.5185	0.9812	1.1281	4.28

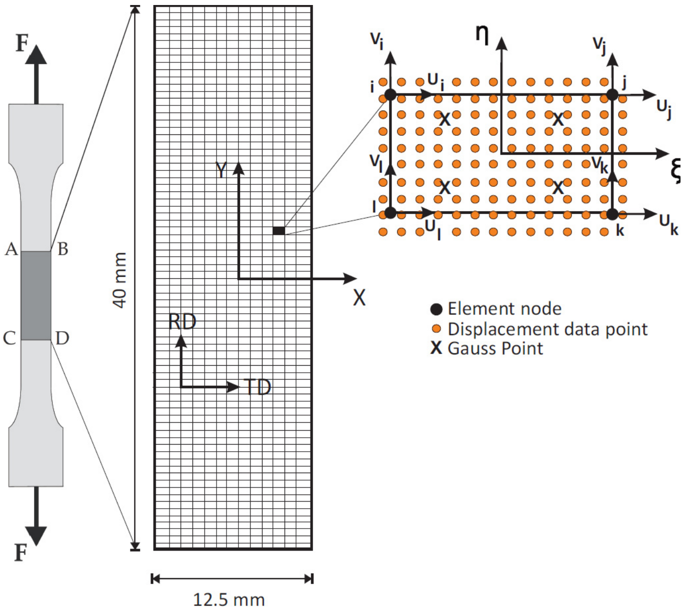

Fig. 1. Post-necking tensile experiment: mesh fitting procedure.

3. Experimental validation

The post-necking tensile experiment was used to identify the post-necking hardening behaviour described by Eq.(2) of a cold rolled interstitial-free steel sheet with an initial thickness of 0.65 mm. A standard tensile test (JIS 13 Type-B) was conducted and the displacement field in the diffuse neck was measured using our in-house stereo digital image correlation system MatchID (2013). The identified p-model is shown in Fig. 2. The maximum uniform strain ε_{max} in the tensile test was about 0.25. The multiaxial tube expansion test machine developed by Kuwabara and Sugawara (2013) enables to expand a tubular specimen under uniaxial tension. The latter test is referred to the uniaxial tube expansion test and this test was used to validate the identified p-model in the post-necking regime, i.e. $\varepsilon_{eq}^{pl} > \varepsilon_{max}$. It can be inferred from Fig. 2 that the uniaxial tube expansion test enables to measure the uniaxial true stress-true strain curve beyond the point of maximum load in a tensile test. The curve is offset to compensate for the effect of pre-strain due to tube fabrication. More detailed information on the multiaxial tube expansion test machine can be found in Kuwabara and Sugawara (2013). Inferable from Fig. 2 is that the identified p-model is in very close agreement with the uniaxial tube expansion test. It can be concluded that the post-necking tensile experiment is successfully validated in the post-necking regime up to ε_{eq}^{pl} =0.35.

4. Comparison with the hydraulic bulge test

In the previous section an independent material test was used to validate the post-necking tensile experiment up to ε_{eq}^{pl}=0.35. To the authors' best knowledge there is currently no other testing method which enables to exert a uniaxial stress state on a test specimen in a strain range larger than attainable by the uniaxial tube expansion test. The results of the post-necking tensile experiment, however, can be compared with the hydraulic bulge test. The bulge test enables probing very large plastic strains under equibiaxial tension. If isotropic hardening is assumed, the equibiaxial stress strain curve from the bulge test is scalable to the uniaxial stress state using the principle of plastic work equivalence. The test material in this study was subjected to a bulge test up to fracture. The diameter of the die opening and the die profile radius were 150 mm and 8 mm, respectively. The equibiaxial stress strain curve is then scaled with a factor 1.12 which was calculated following ISO/FDIS 16808. Fig. 3 shows the scaled bulge test along with the identified p-model.

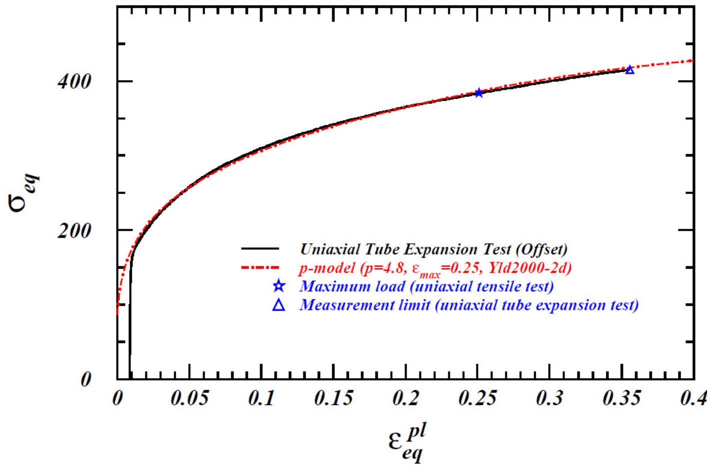

Fig. 2. Experimental validation of post-necking tensile experiment.

Inferable from this figure is that in the pre-necking region the scaled bulge test is in close agreement with the p-model which confirms the hypothesis with respect to isotropic hardening. A significant discrepancy, however, is found at larger plastic strains. Unlike the scaled bulge test, the p-model predicts a decreased hardening rate at very large plastic strains. This suggests that isotropic hardening is no longer valid, and, consequently, that post-necking strain hardening depends on the stress state. Other researchers have also found a decreased hardening rate during diffuse necking of sheet metal. Kajberg and Lindkvist (2004) found that their piecewise linear hardening model predicted almost negligible strain hardening at large plastic strains for two hot rolled steels. Dunand and Mohr (2010) used a piecewise linear hardening model and found for TRIP steel that the hardening modulus decreased in the post-necking regime. Nevertheless, independent experimental validation of this phenomenon is currently lacking. In this regard, the recent work of Iadicola (2011) is very interesting. Iadicola developed a unique experimental set up which enables to simultaneously measure the strain state and the stress state within the diffuse neck using digital image correlation and X-ray diffraction, respectively.

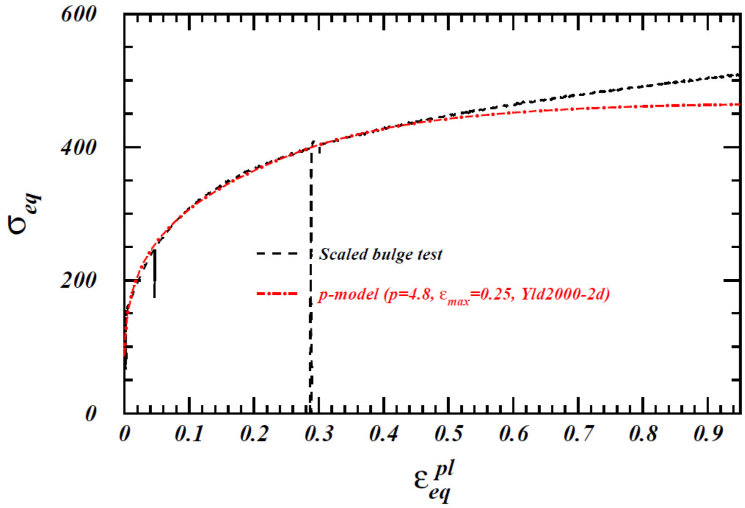

Fig. 3. Comparison between post-necking tensile experiment and hydraulic bulge test.

5. Conclusions

In this paper an alternative method to identify post-necking strain hardening behaviour of sheet metal is presented. The proposed method is successfully validated using an independent material test. For that purpose, the uniaxial tube expansion test was used to obtain uniaxial strain hardening behaviour beyond the point of maximum load in a tensile test. A phenomenological hardening law which enables to disentangle pre –and post-necking hardening behaviour is proposed. Finally, the proposed method is compared with the hydraulic bulge test. This revealed a significant discrepancy at very large plastic strains. Unlike the bulge test, the proposed method predicts a decreased hardening rate deep into the post-necking regime. While not conclusive, this result suggests differential work hardening in the post-necking regime.

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