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On the prediction of failure in metal sheets with special reference to strain path dependence

Kjell Mattiasson [a,b,*], Johan Jergéus [b], Paul DuBois [c]

[a] Department of Applied Mechanics, Chalmers University of Technology, 412 96 Göteborg, Sweden
[b] Volvo Cars Safety Center, Department 91430, 405 31 Göteborg, Sweden
[c] Hermes Engineering, Belgium

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ABSTRACT

Prediction of failure in metal sheets is an important topic for the sheet forming community, as well as for the automotive crash community. The word 'failure' can have different meaning for different individuals within these communities. Methods for failure prediction within this area can either focus on the prediction of plastic instability (necking), or on the actual fracture phenomenon. The pros and cons of these approaches are discussed in this paper. The current authors have chosen to favour methods for necking prediction. The traditional method for necking prediction is to use a limit curve in the principal strain space (FLD). The great disadvantage of this approach is that it is only applicable for linear strain paths. In fact, the necking phenomenon can be shown to be strongly strain path dependent. In the current report, four different numerical methods for instability prediction are discussed, and compared in applications to some simple problems involving broken strain paths. It is shown that these methods can yield dramatically different results in some particular cases. Based on the findings of this study, the paper concludes with some recommendations for how the failure prediction problem best can be handled in industrial sheet forming and crash simulations.

1. Introduction

Metal sheets normally fail after extensive plastic tensile deformations. The phenomenon is termed *ductile fracture*, as opposed to *brittle fracture*, which can be encountered in e.g. glass, ceramics, concrete, and so on. Fracture is often preceded by a strong localisation of strains to a narrow band (neck) with a substantially reduced thickness. The fracture phenomenon itself can be caused by, or influenced by, the formation, growth, and, finally, coalescence of microvoids in the material. This deterioration of the material is known as damage growth, and interacts with the formation of the neck. With increasing stresses in the fractured zone the crack subsequently starts to propagate.

Sheet forming processes have to be designed so that necking and fracture in the material are avoided during the course of the forming operation. For several decades the Forming Limit Diagram (FLD) has been the tool used by the sheet forming industry, in order to evaluate the risk for failure in forming operations. The FLD involves a limit curve, the forming Limit Curve (FLC), in the principal strain space. The FLC is determined experimentally by subjecting sheet metal samples to different linear strain paths up to necking, and eventually fracture. A point on this limit curve represents the point of incipient necking for the corresponding linear strain path. Strain states represented by points on the FLD situated above this limit curve are thus judged as being unsafe.

It should be emphasised that in sheet forming contexts, the focus is on the onset of necking, and not on the actual fracture phenomenon. The reason for this is that a part with a neck, even if it has not fractured, cannot be approved. Normally a certain safety margin to the FLC is required in order to account for variations in the process. For obvious reasons, nor is there any need to be able to predict the crack propagation in the sheet material.

The behaviour of the sheet material in a car crash resembles very much the behaviour of the material in a forming operation. The main difference is that the velocities are higher in a crash event. This fact does not, however, alter the fundamental material behaviour. The materials used in car bodies 5–10 years ago were usually ductile enough to withstand the resulting deformations in a crash event without fracturing. The trend in car body design is, however, to introduce more high strength materials in order to reduce the weight, and at the same time preserve, or even improve, the crash performance. The drawback of these materials is that there ductility is substantially lower that of the previously used materials.

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[*] Corresponding author at: Volvo Cars Safety Center, Department. 91430, 405 31 Göteborg, Sweden. Tel.: +46 31 596007.

E-mail addresses: kjellm@chalmers.se, kmattias@volvocars.com (K. Mattiasson), jjergeus@volvocars.com (J. Jergéus), paul.dubois@gmx.net (P. DuBois).

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A consequence of the low ductility of these high strength materials is that fracture in highly strained parts might very well be anticipated during a car crash. It is, thus, of utmost importance that the fracture phenomenon can be simulated in an accurate way by the CAE tools used for crash simulations. This topic has therefore, not surprisingly, attracted a lot of attention from researchers in this field during the last few years. Since the research field is relatively young, the problem is approached from many different angles of incidence by different researchers. It is interesting, though, to observe that the various approaches can be divided in two groups based on two fundamental different ways of thinking. On one hand, it seems like people from the crash community prefer approaches focusing on the actual fracture phenomenon, without considering the fact that it can be preceded by a considerable strain localisation. On the other hand, people with a background in the sheet forming community like to stick with their traditions, and consider the incipient necking strain to be the limit for what the material can sustain.

CrachFEM is a program module for failure risk evaluation that works as an add-on to the most well-known FE-codes for crash and sheet forming simulation. Three failure modes are considered separately: Two fracture modes together with plastic instability (necking). It should, thus, be observed that necking is considered to be a criterion for failure. It is probably connected to the fact that CrachFEM originally was developed with focus on sheet forming applications. CrachFEM together with the FE-code LS-DYNA has been used for a few years at Volvo Cars for failure risk evaluation in car crash simulations. Experience has shown that plastic instability is by far the most common failure mode in these applications, even for ultra-high strength steel qualities like press-hardened boron steel.

In the present paper the differences between failure risk evaluation based on fracture and plastic instability, respectively, will be further elaborated. Based on our previous experience, the focus of this report will be on necking prediction. It can be shown that the strain state corresponding to incipient necking is strongly dependent on the strain path up to the necking point. The use of a static FLD as a tool for evaluating the risk for necking failure is, thus, restricted to linear strain paths. CrachFEM has a very advanced algorithm to account for nonlinear and broken strain paths. The drawback of this algorithm is that it is very costly to use in terms of computing time.

It has been shown that by transforming a limit curve in principal strain space, i.e an FLC, to the principal stress space, a limit curve is obtained that is much less sensitive to the strain path. For various reasons, however, this concept has never received any widespread practical use. It has recently been shown that the experimental FLC can be transformed to other variable spaces, but still retaining the strain path independence properties of the stress based limit curve. Some of these alternative limit curve representations seem to have the potential of becoming practical tools for failure risk evaluation.

In this report these alternative approaches will be examined from a theoretical perspective, and their potentials and limitations will be elaborated. Numerical results from the various approaches will be compared with each other and with results from CrachFEM in applications to simple examples involving broken strain paths.

2. Necking and fracture

2.1. Fracture modes

Metal sheets break in one of the two following macroscopic fracture modes:

- Ductile *normal* fracture
- Ductile *shear* fracture

Ductile normal fracture is the result of void nucleation, void growth and void coalescence. This phenomenon is known as damage growth. Ductile shear fracture is due to shear band localisation, which possibly may be initiated by the formation of voids. Shear bands may appear through the thickness of the sheet or in the plane of it. The actual fracture mode depends on the strain path, and on the microstructure of the material in question.

2.2. Plastic instability

In a uniaxial tensile test of a metal sheet specimen, the deformation field is homogeneous in the specimen up to a certain point, after which the deformations become inhomogeneous, and a neck is formed in the width direction of the specimen. This phenomenon is known as diffuse necking. The formation of the diffuse neck coincides in time with the force maximum. The limit for the diffuse necking is, thus, well defined in a uniaxial tensile test.

A sheet specimen subjected to an arbitrary bi-axial stretching mode will exhibit a corresponding behaviour, i.e. at a certain magnitude of deformation the strain field will become inhomogeneous. In contrast to the uniaxial case, this phenomenon is not easily observable, nor is there any clear definition of the diffuse necking limit.

In a displacement controlled test, there is a gradual increase in strains after the point of diffuse necking. At the same time there is a gradual change in the strain distribution. Finally, strains will localise at a narrow band with a marked thickness reduction. The width of this neck is of the order of the sheet thickness. This phenomenon is called localised necking. When the neck starts to form, the stress field in this area turns from plane stress to a 3D one. Since the subsequent strain growth concentrates in this small neck, the strain magnitude in the neck grows rapidly, accompanied by a damage growth. Finally, the material breaks in a normal or shear fracture mode.

2.3. The implications of plastic instability on a finite element solution

It should be emphasised that the plastic instability phenomena are merely dependent on the material's elastic-plastic properties. Consequently, in numerical models for e.g. sheet forming or crash simulations, the quality of the material modelling is decisive for how well these phenomena can be predicted. A phenomenological elastic–plastic material model consists of several ingredients, like a yield condition, a plastic hardening curve, a hardening law, and a strain rate dependency law. Each one of these model ingredients is of vital importance for the quality of the plastic instability predictions. This subject has been treated in numerous scientific papers, i.e. by the current authors in [1–7]. The subject of material modelling will not be treated further in the current report, but its importance for an accurate prediction of necking instability should be kept in mind by the reader.

A uniaxial tensile test can be simulated correctly with one single row of finite elements over the width of the specimen, as long as the deformations are homogeneous, i.e. up to the point of diffuse necking. After diffuse necking it takes several elements over the width to correctly capture the evolving strain distribution. To finally be able to model the incipient localised necking, the mesh size has to be of the order of the width of the neck, i.e. of the order $0.5t$–$1.0t$, where t is the sheet thickness. When the neck starts to form, and the stress state turns into a 3D one, it takes a mesh with solid elements and ten or more elements over the sheet thickness to further capture the behaviour in the neck. In a case with a general bi-axial load, the situation is the same, i.e. it takes a fairly fine mesh to model the strain distribution after diffuse necking, and it takes an extremely fine mesh to capture the incipient localised necking.