SOME OBSERVATIONS ON FAILURE PREDICTION IN SHEET METAL FORMING

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ABSTRACT

This paper presents results from a FE-study on failure prediction in ductile metal sheets. The studied material, a DP600 dual phase steel, is used throughout the study. The effects of variation of element sizes, material parameters, and friction are shown and discussed. Also results from simulations of in-plane and out-of-plane tests are compared and discussed.

KEYWORDS:

Sheet metal, Forming Limit Curve, strain localization, necking, ductile failure

INTRODUCTION

The Forming Limit Curve, (FLC), is commonly used as a failure criterion in sheet metal forming. The FLCs are usually determined experimentally, although there are quite a few problems connected to such procedures. The experiments are time-consuming and costly, and are not so easily realized. Therefore, the goal is to be able to produce FLCs by using other methods. Herein are discussed some issues in connection to the use of the Finite Element Method (FEM) for this purpose. In an ongoing project with the purpose of improving the quality of sheet metal forming analysis, some work on failure analysis has been reported by the current authors in [1-3]. In these reports various procedures for limit strain prediction are discussed, such as experimental methods, theoretical/analytical methods and FE-simulations. Herein the focus is on the use of the FEM for this purpose. Special attention is paid to the effect of element size, the importance of material modelling, and the impact of friction on the failure behaviour. It is shown that the limit strains from the FE simulations are dependent on the resolution of the finite element mesh, especially in the vicinity of the neck. Furthermore, it is shown how material data, not commonly provided in materials testing, have some impact on the results, and also how small changes in friction also impact the origin of the failure. In order to compare the resulting limit strains from an out-of-plane test, and an in-plane test, respectively, both Nakazima tests and simplified Marciniak tests are simulated. Considerable differences between the predicted FLC results by the various modelling options are observed, facts that illustrate the complexity of the problem. Among studies within the same scope as the present one can e.g. be mentioned the one by Moshfegh [4].

MATERIAL DESCRIPTION

To fulfil the purpose of the current investigation, it has been considered enough to study one single material. A DP600 dual phase steel was thoroughly characterized by uniaxial tension tests in three directions, together with a viscous bulge test. These tests gave as a result the plastic hardening curve shown in Figure 1, and the material data presented in Table 1. The yield condition used in this study involves eight coefficients. These coefficients are determined from the eight material parameters presented in Table 1. The yield loci for the material in the principal stress plane are displayed in Figure 2.

The material model used in LS-DYNA [5] is the *MAT_BARLAT_YLD2000 (material type 133). This material model is using the Yld2000 yield criterion by Barlat et al. [6]. The shape of the yield surface is determined by the eight parameters mentioned above. The exponent m in the yield function is given the value 6 for the DP600 material. This choice of m might be revised, as experience by the current authors, and by other colleagues in the field, indicate that the choice $m=8$ gives a better the description of the behaviour of this material. The result for $m=8$ is shown for comparison in this paper.

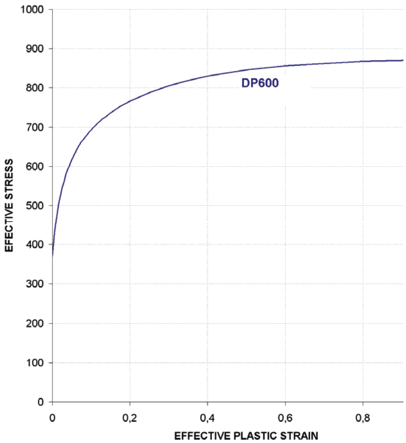


Figure 1. Plastic hardening curve

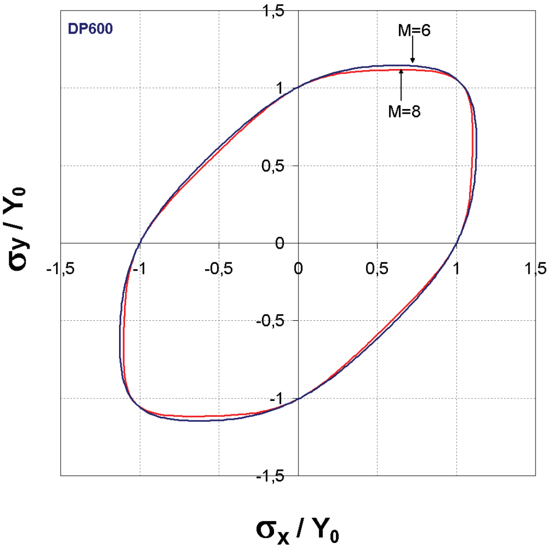


Figure 2. Yield loci

Incorporated in the material type 133 is also an option to include mixed isotropic/kinematic hardening behaviour. To demonstrate the effect of mixed hardening, an index of 0.35 is used, where the mixed index equals 0 models pure isotropic hardening. The value 0.35 for the mixed index is based on results from Lee et al. [7]. In this material model strain-rate behaviour may also be included using a Cowper-Symonds model. The strain rate option is not used in this the study, but the effects of strain rate will be investigated in the near future with the FE models applied herein using the recent findings in Mattiasson et al. [8].

Table 1: Material properties for the DP600 material

Material	σ_0 (MPa)	σ_{45} (MPa)	σ_{90} (MPa)	σ_b (MPa)	R_0	R_{45}	R_{90}	R_b
DP600	370	365	373	382	0.99	0.97	1.14	0.90

NUMERICAL MODELS

The die geometries used in the FE-study are the same as the ones used in the experiments presented in Mattiasson et al. [3]. The geometries used for the Nakazima and Marciniak tests are shown in Figures 3 and 4, respectively. In both cases the punch diameter is 100 mm, and the corner radius in the simplified Marciniak model is 20 mm. Instead of the intermediate washer used in the original Marciniak test, there is a hole with a diameter of 50 mm in the punch, making it possible to avoid contact between the blank and the punch in the expected failure area. Also thin plastic films with oil in-between are used in the simplified Marciniak test. The same die is used for both test set-ups with an opening diameter of 105 mm and a die corner radius of 16 mm. A typical element length for the radii in the tools is 0.7 mm.

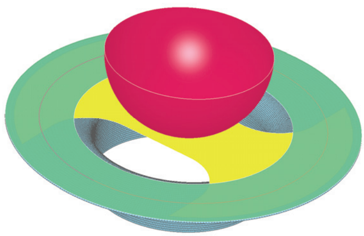


Figure 3. Nakazima geometry.

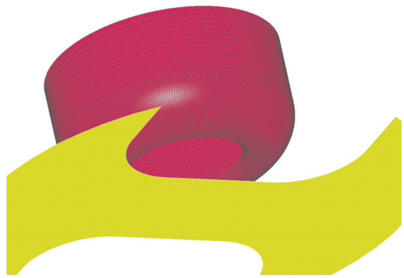


Figure 4. Simplified Marciniak geometry.

The blank is modelled with the fully integrated type 16 shell element in LS-DYNA, The sheet thickness is 1 mm. In the 50 by 50 mm centre area of the blank, the element length is 0.75 mm. At a punch depth of 17.9 mm this area is adapted uniformly one level, and then this mesh is used throughout the simulation. This is the base model of the blank. The same blank geometry is used throughout this investigation, i.e. only one specimen width is studied.

It is believed that the method used, and the conclusions drawn, apply for all practical specimen widths necessary to use for a complete determination of a FLC. In no case in the simulations of the in-plane test, failure could be detected prior to a punch depth of 20 mm. For the base model, the limit strains were evaluated at a punch depth of 21.4 mm. In the out-of-plane test, failure occurs when the punch depths exceed 28 mm. Therefore, the uniform adaptation described above could have been performed later than in the in-plane case. This was, however, not done, resulting in somewhat longer calculation times compared to the out-of-plane case.

The base blank model is used in most cases with the following exceptions:

- A coarse mesh with 1.5 mm elements in the centre area.
- Original element size (0.75 mm) used throughout the simulation.
- A two level uniform adaptive mesh refinement.

In two cases, the initial element thickness is randomly distributed within the range 0.998-1.000 mm. In one case, all the elements in the area are considered to be candidates for this random distribution, while in the other case only 10 percent of the elements are candidates for this option. This random thickness distribution is accomplished by means of a MATLAB ([9]) code. A more sophisticated method for a strategic choice of seed elements and limitations on thickness differences between adjacent elements is going to be developed; Moshfegh [10].

OBSERVATIONS

In Figure 5 the results for all simulations made for both the simplified Marciniak test and the Nakazima test are shown. The solid line in Figure 5 is the FLC resulting from a Marciniak-Kuczynski (M-K) analysis with f_0=0.998 taken from Mattiasson et al [3]. In general, the out-of-plane test yields significantly higher minor strains than the in-plane test, while the major strains for comparable options are similar. This implies that the predicted FLC by an out-of plane test is higher than a FLC predicted by an in-plane test. Furthermore, friction has a more pronounced influence on the results for the Nakazima test than for the simplified Marciniak test. As expected, the influence of mixed material hardening is limited for the Nakazima test, while some impact of this phenomenon is observed in the simplified Marciniak test. At least for the Marciniak test it therefore seems advisable to determine the material's mixed hardening properties in order to determine the complete FLC. A change of the exponent *m* from 6 to 8 (see "MATERIAL DESCRIPTION" and Figure 2) has some additional impact on the limit strains. In this case the Nakazima test is the most sensitive one. To get a precise definition of the yield locus, including the determination of the exponent *m*, a number of different biaxial material tests may have to be performed.

In the simulations of the simplified Marciniak test four different element sizes are used: 1.5, 0.75, 0.37 and 0.19 mm, respectively. There is a very strong influence on the limit strains of the element sizes. For the larger element sizes it is not possible to resolve the limit strains in the vicinity of the neck. The neck becomes quite diffuse and is spread over a wide area. This makes it very difficult to define a limit strain. In Figures 6 and 7 the strain gradients are plotted for the different element sizes. (CG in the figure means "centre of gravity"). The gradients are shown for two cases; at maximum punch force and at 0.5 mm punch depth before the maximum load. The gradients are evaluated in the elements adjacent to the failed element. In one case, for the 0.19 mm element mesh, two curves are shown. The short curve represents the limit strain gradient averaged from elements on both sides of the failed element.

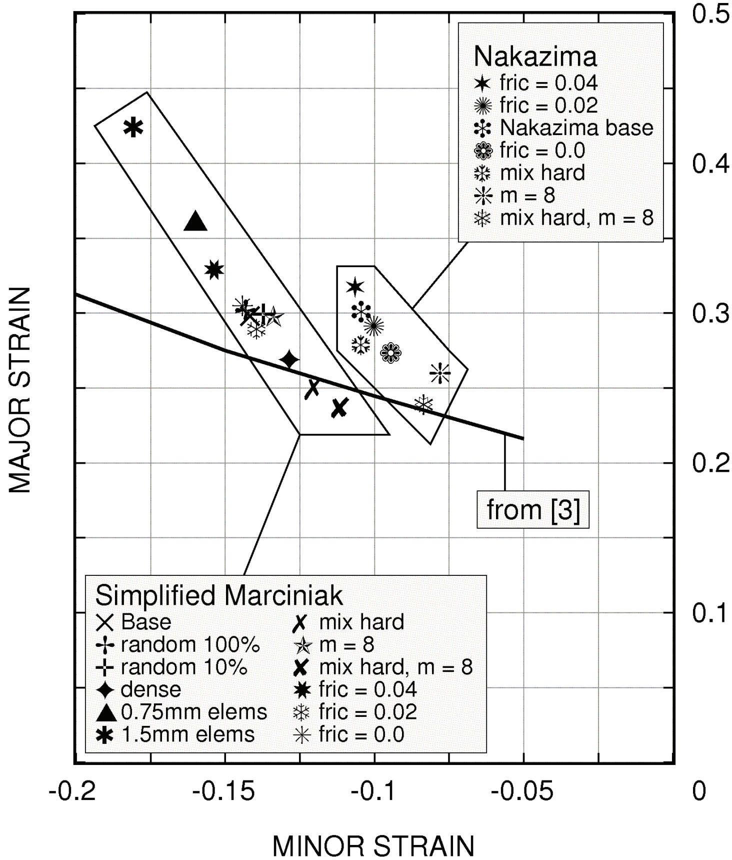


Figure 5. Limit strains for the 50 mm width specimen with some variation of input parameters

At about 4 mm away from the neck, the difference in the limit strain levels is reduced and the element size dependence is now limited. Still, it is recommended to use a dense mesh in the area where failure is to be expected. In Figure 8a-d below, a sequence of pictures shows how the neck in the base model for the simplified Marciniak test evolves. The fringe plots show the thickness distribution ranging from 0.7 mm to 0.94 mm. In picture b the thickness distribution at maximum punch load is shown. The pictures a, c, and d show the corresponding plots 0.5 mm before, 0.5 mm after and 1 mm after, respectively, relative to this event. Finding the failure pattern and location of the elements where limit strain shall be evaluated is an inverse process in some sense. When the critical elements are located, the time histories for these elements are plotted and evaluated. The formation of the cross pattern at failure for the in-plane test is in good qualitative agreement with experimental findings according to Figure 10a.

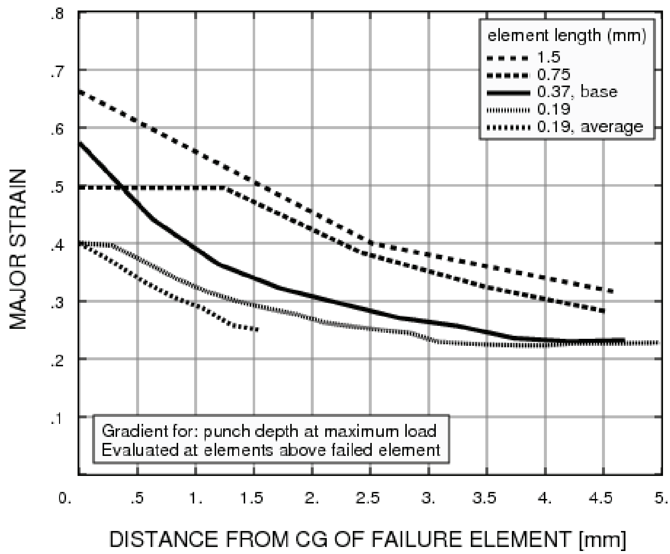


Figure 6. Major strain gradients for punch depth at maximum load

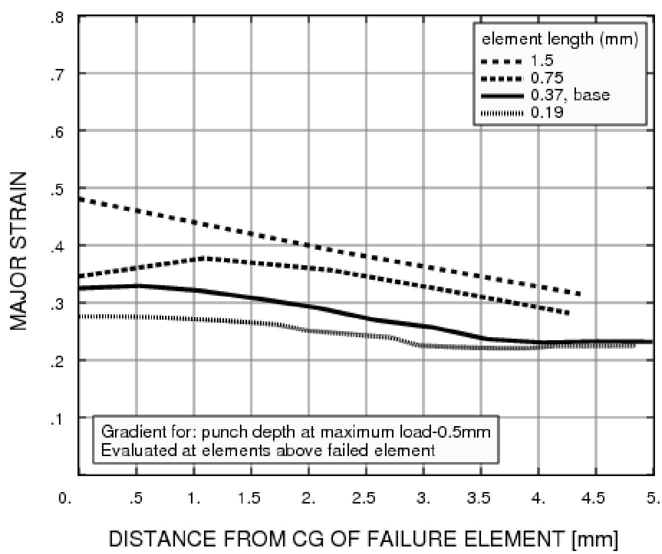
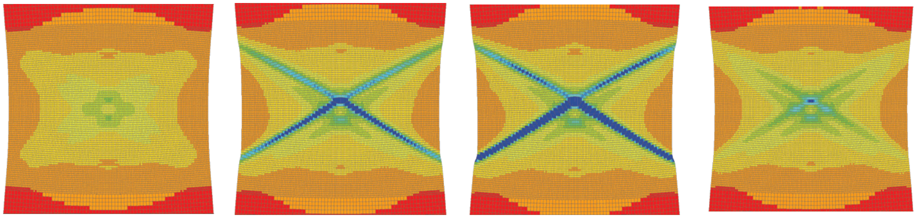


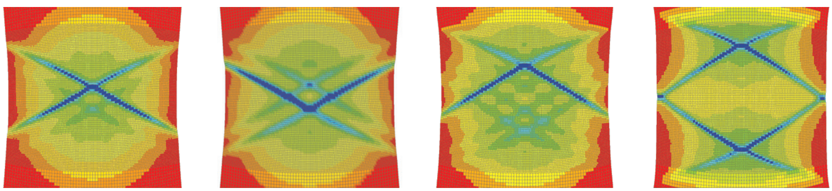
Figure 7. Major strain gradients for punch depth at maximum load - 0.5 mm



(a) 0.5 mm before (b) at maximum load (c) 0.5 mm after (d) 1 mm after

Figure 8. Necking formation for the in-plane test (simplified Marciniak test)

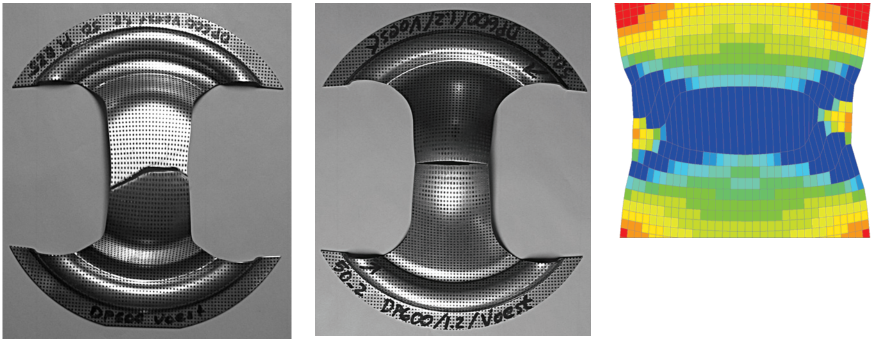
In Figure 9a-d it is demonstrated how small changes in the friction coefficient μ rapidly moves the failure area away from the pole centre of the punch in the Nakazima test. This is not the case in the simplified Marciniak test.



(a) μ=0 (b) μ=0.01 (c) μ=0.02 (d) μ=0.04

Figure 9*.* Failure area position dependence of friction for the Nakazima test

The crack in the out-of-plane experimental test is shown in Figure 10b. The simulation result is taken from the base run for the Nakazima set-up. How the failure evolves in this calculation can be seen from a snapshot depicted in Figure 9b. At first sight, the agreement between the numerical analysis and experiment is not the best. However, a closer inspection of Figure 9b reveals two necking zones in form of two crosses, and the neck evolves in a v-shape. This, together with the initial two crosses, shows the complexity of the neck formation and demonstrates that the neck might develop along several paths. In a simulation performed with a 1.5 mm element mesh in the centre area, otherwise same data and options as the base Nakazima setup, the failure occurs as depicted in Figure 10c. This is seemingly in more agreement with the experimental result. These findings further enhance the point of view that this set-up might be too sensitive for small imperfections to be the experiment of choice for the determination of FLCs.



(a) (b) (c)

Figure 10. (a) Marciniak and (b) Nakazima test specimen and (c) Nakazima test, failure formation from calculation using 1.5 mm elements.

CONCLUSIONS

- A dense mesh must be used in order to resolve the limit strains in the vicinity of the narrow neck.
- The material characterisation needs to be further improved to facilitate a detailed determination of the yield locus shape. To determine and include mixed material hardening will increase the precision of the simulation.
- In some cases friction is a very sensitive variable. To determine forming limits it is advocated to use experimental set-ups where the frictional behaviour plays a subordinate role.

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