

Models for strain path independent necking prediction in LS-DYNA

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1 Introduction

Failure in sheet metal can be caused by one of, or a combination of, the following mechanisms: ductile fracture, shear fracture and plastic instability (necking). Ductile fracture is caused by the initiation, growth and coalescence of voids in the material during plastic straining, commonly referred to as damage growth. Micro defects can also lead to through-thickness shear fracture in the sheet metal.

There are several different scenarios involving the above mechanisms leading to material fracture. In ductile materials fracture is normally preceded by the formation of a neck in which the strains localizes after further loading. This neck has the width of the order of the sheet thickness. After the initiation of the neck the strains and the damage inside the neck start to grow rapidly, and finally the material breaks according to one of the mechanisms described above. The incipient necking is in this case also referred to as “plastic instability” as the phenomenon is solely dependent on the plastic properties of the material. It should be observed that the incipient necking phenomenon can be captured by a plane stress shell FE model if the elements are small enough, i.e. of the order of the sheet thickness. After the formation of the neck the stress state in the neck turns into a 3D one, and a highly refined 3D FE-model is required to be able to simulate the post-necking behaviour.

Another possible scenario is that damage starts to grow before the formation of a neck. The softening of the material can then speed up the neck formation. In some less ductile materials, e.g. some aluminium alloys and austenitic stainless steels, crack formation can even take place before strain localization.

Experience has, however, revealed that incipient necking is the by far the most common failure mode in sheet metal forming applications, as well as in automotive crash applications. The current paper will therefore be focused on the prediction of necking, and especially on methods for handling the strong strain path dependence of this phenomenon.

The LS-DYNA code is used by Volvo Cars for performing car crash simulations. Currently the third-party module CrachFEM from the Matfem company, which is linked to the LS-DYNA code, is used for performing material failure analyses. However, lately several models for performing necking as well as fracture simulations have been implemented in LS-DYNA. It is the object of the current paper to give an overview of these options and to present results from some evaluations of these models.

2 Methods for necking prediction

2.1 The Forming Limit Diagram concept

The Forming Limit Diagram (FLD) concept for necking risk evaluation is about 50 years old. In an FLD a limit curve in the principal strain space, the Forming Limit Curve (FLC), indicates an upper limit for allowable strains with respect to necking failure. An FLC is constructed from experiments in which sheet metal test pieces are subjected various loading conditions, leading to almost straight strain paths, up to localized necking. By measuring the limit strains an FLC for the material can be constructed.

The FLD concept was originally developed for performing forming feasibility studies in the press-shop. However, since the introduction of FEM as a tool for performing numerical sheet forming simulations in the mid 1990's, the same concept has been used for evaluating the failure risk in the post-processing of FE simulations. A reason for the popularity of the FLD concept is that it is very intuitive and easy to understand. The FLC describes exactly the strains that are measured on the formed blank, or are displayed on the computer screen at the post-processing of a FE simulation.

In spite of its popularity the FLD concept has many drawbacks. The most serious one is probably its strain path dependency. As described above, the FLC is constructed by means of experiments leading to almost straight strain paths. However, in real forming operations, as well as in car bodies subjected to crash loads, the strain paths can be strongly nonlinear, and even broken. In such cases the FLD is completely incapable of predicting the correct necking failure risk.

2.2 On the definition of “incipient necking“

It should be emphasized that there does not exist any clear and unambiguous definition of the phenomenon called “incipient necking“. There do exist numerous definitions of the phenomenon that do not exactly coincide. This should, however, not be a big problem, if one bears this in mind, and understands that the prediction of incipient necking is not an exact science. Problems can arise if comparisons between different materials with respect to formability are performed based on the appearances of their FLDs. If these FLDs are experimentally determined by different laboratories using different definitions of the notion of incipient necking, such comparisons can be highly misleading. To circumvent that problem there have been, and still are ongoing, work to standardize the execution of, and interpretation of material tests. The problems of achieving comparable FLCs at different laboratories have been discussed by Col [1].

2.3 The Forming Limit Stress Diagram

The concept of the Forming Limit Stress Diagram (FLSD) was first introduced by Arrieux et al. [2] in 1982. They showed that by transforming the normal FLC to the principal stress plane, a limit curve that was considerably less sensitive to the strain path could be achieved. The advantages of the FLSD concept have in later years been strongly emphasized by Stoughton et al. [3]-[6].

Despite its documented advantages the FLSD concept has not found any wide spread application among practicing engineers. One reason for this could be that stresses are perceived as being less intuitive variables than strains, and cannot be directly measured in experiments. Another reason is that stresses are less accurately predicted than strains in FE simulations. Calculated stresses do also show a tendency for an oscillating behaviour, especially in dynamic explicit simulations.

2.4 Forming limit curves in other variable spaces

It can be shown that the same strain path independence that has been demonstrated for the stress based FLD also can be obtained in other variable spaces. Zeng et al.[7] and Zhu [8] have proposed a limit curve with respect to effective plastic strain as a function of the ratio between the minor and the major principal plastic strain rates. In the stress based FLD it is only the stress state in the final state that is of any concern. The histories of stress and strain are insignificant. In the same manner, in the proposed method it is only the magnitude of the effective plastic strain together with the plastic flow direction at the last stage of deformation that is of importance. The current limit curve in terms of effective plastic strain is considered to be more easily interpreted by the practicing engineers than a corresponding limit curve in the stress space.

The fracture phenomenon is, in contrast to the metal plastic behaviour, pressure dependent. It is therefore common practise to express fracture criteria as functions of stress triaxiality. Some writers do therefore prefer to express also the necking condition in terms of effective plastic strain and stress triaxiality. Such a limit curve will inherit the same path independent properties as the other limit curve alternatives discussed above. Stress triaxiality is in the current context defined as the ratio between mean stress and effective stress.

2.5 On the role of isotropic hardening

The path independent properties of some of the previously discussed forming limit concepts can be shown to presuppose the assumption of isotropic hardening. It can also be shown that the path independency is a direct consequence of this assumption. A discussion on this subject can be found in Aretz et al. [9]. In case of assumed kinematic or distortional hardening the path dependency of these forming limits is, thus, not preserved. One should be aware of the fact that, the more two consecutive strain paths deviate from each other, the less the assumption of isotropic hardening is justified. The path independency that seemingly is an inherent property of some of the forming limit concepts is, thus, not a true path independency in practice.

2.6 Post-necking behaviour

As discussed in the introduction, the behaviour inside the neck after initiation is very difficult to capture in a FE simulation. It takes both a fine 3D model and a material model including damage. For high strength and ultra high strength steel, fracture follows very soon after neck initiation. For some aluminum alloys there can, however, be an extra, noticeable deformation in the neck before fracture. Normally incipient necking is considered as a fracture criterion in both sheet metal forming simulations, as well as in automotive crash simulations. Such an assumption is always conservative. There have been some attempts presented in the literature to model the post necking behaviour by various phenomenological models. Examples of such attempts can be found in e.g. Aretz et al. [9] and Kessler et al. [10]. In the current study no post-necking effects have been considered.

3 Analytical methods for FLC prediction

3.1 Introductory remarks

There exist a few methods for predicting the FLC based on the plastic material properties of the sheet. Two of these methods will be very briefly described here. These are the Marciniak-Kuczynski (M-K) method and the Maximum Force Criterion (MFC). The reason for mentioning these methods is that they will have some relevance for the rest of the paper.

3.2 The Marciniak-Kuczynski method

The Marciniak-Kuczynski (M-K) approach [11] is probably the most well-known and widely used method for analytical FLC prediction. In this approach a sheet sample with a geometric imperfection in form of a band perpendicular to the principal tensile direction is studied. The initial relation between the thicknesses in the groove and in the homogeneous part is determined by a prescribed "imperfection factor". The strain is prescribed incrementally in the homogeneous region along linear paths. Stresses and the strain increments are determined so that force equilibrium is maintained. The necking limit is supposed to be reached when e.g. the strain rate in the groove is several times bigger than the strain rate in the homogeneous region. The strains in the homogeneous region are then considered to be the limit strains. The M-K approach was originally developed for predicting limit strains on the right hand side of the FLD (stretch side). In this range the orientation of the imperfection band can be assumed to be constant. The M-K approach was later on extended by Hutchinson and Neale [12] to also consider negative strain ratios. In the extended approach the imperfection band is assumed to have a certain inclination to the 2-direction. For every strain path the value of the inclination angle leading to the lowest value of the limit strain has to be determined. The primary drawback of the M-K approach is that the predicted FLCs, to a great extent are depending on the choice of the imperfection factor.

3.3 The Maximum Force Criterion

According to Swift's Maximum Force Criterion (MFC), diffuse necking is reached when the maximum force of a stretched, infinitesimal sheet element reaches a maximum under a linear strain path. Assuming rigid-plasticity, volume constancy, and constant strain ratio, the following condition for *stable* plastic straining can easily be derived:

$$\frac{d\sigma_1}{d\varepsilon_1} \geq \sigma_1 \quad (1)$$

Hora et al. [12], [14] extended the criterion, combining it with the understanding of the fact that the stress/strain state is rotating towards plane strain in the neck region. They derived an analytical expression for the limit strain and called the criterion "The Modified Maximum Force Criterion" (MMFC).

In the MMFC an approximations had to be introduced in order to reach an analytical expression for the limit strains. This approximation had a strong negative effect on the accuracy of the method. In order to improve the accuracy of the method, one of the current authors and colleagues, Mattiasson et al. [15]-[17], suggested an alternative approach based on the fundamental equation (1) of the MFC, but in which no further approximations were introduced. This was shown to have a significant influence on the resulting FLCs.

Compared to the M-K approach, the advantage of the current method is that the uncertainty associated with the imperfection factor can be avoided.

4 CrachFEM and the Crach algorithm

CrachFEM is a program module for failure risk evaluation that works as an add-on to several of the most well known codes for crash and sheet forming simulation. CrachFEM considers three failure modes separately:

- Plastic instability (necking)
- Ductile normal fracture
- Shear fracture

In the following only the first one of these failure criteria will be described. The module for instability prediction, the Crach algorithm, is based on the M-K approach with a refined description of the cross-section of the neck. It is especially developed to be able to account for nonlinear strain paths. The imperfection factor is calibrated from the limit strains of a uniaxial tensile test. The material model used in the Crach algorithm is based on a Hill'48 anisotropic yield condition and an isotropic-kinematic hardening law. Strain rate dependency is also considered. Even if the plastic hardening and the strain rate dependency for the material description used for the FE-solution are based on tabulated data, the Crach algorithm uses analytical descriptions for these properties. The yield condition can also be a completely different one in the FE-solution.

At prescribed intervals during the solution process, the plasticity problem is solved inside the neck based on the stresses outside the neck. When equilibrium no longer can be established, incipient necking is assumed to prevail. The most dangerous initial orientation angle of the neck must be found every time the Crach algorithm is activated.

To sum up, the Crach algorithm is probably the most advanced method available for local instability detection. The main shortcoming of the algorithm is that it is based on the M-K approach, whose predictions rely heavily on the assumed imperfection factor. Another drawback is that it internally uses a Hill'48 yield condition. It is a well known fact that strain localization is strongly dependent on the shape of the yield locus, especially in the stretch region. The use of one single analytical expression for the hardening curve has in some cases also turned out to be a too rude approximation. Another serious drawback of CrachFEM is that it, due to its high complexity, is very computationally demanding.

Results from CrachFEM will be used in the following evaluation studies

5 Material used in the current study

The sheet material used in the current study is a hot formed boron steel. This type of material is commonly used in modern cars. It is characterized by very high strength and low ductility. Due to its low ductility, the material might break in severe crash load cases. It is thus of utmost importance that critical areas in the car body can be detected and resolved during the development phase, which nowadays rely heavily on FE-simulations. In spite of the material's low ductility, it has become evident that plastic instability is the by far most commonly appearing and most dangerous failure mode.

The hardening curve of the current boron steel is displayed in Fig. 1. In the Crach algorithm this hardening curve is described by an exponential function with the exponent $n=0.087$. The anisotropy for

this material is insignificant, and an isotropic von Mises Yield condition is therefore used. The strain rate dependency is also insignificant.

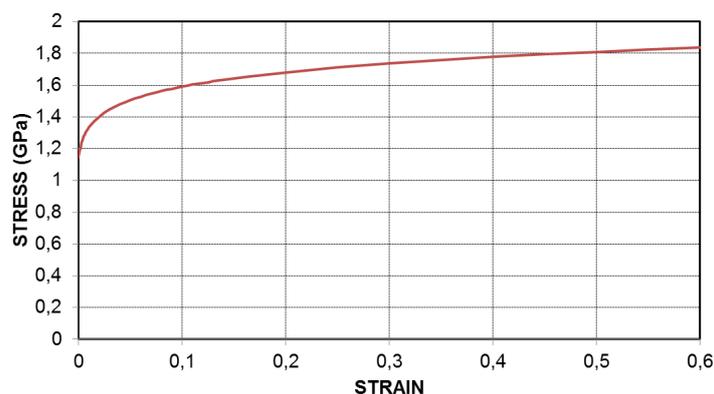


Fig. 1: Hardening curve for the boron steel used in the current study

6 An evaluation of the strain path sensitivity of two FLC modelling concepts

6.1 Results obtained with the Maximum Force Criterion

The MFC has been used to create forming limit curves in five different variable spaces: (a) Principal strain space ϵ_2/ϵ_1 (traditional FLD), (b) Effective plastic strain vs principal plastic strain ratio ($\text{dep}_2/\text{dep}_1$), (c) Effective plastic strain vs principal strain ratio ($\text{deps}_2/\text{deps}_1$), (d) Effective plastic strain vs stress triaxiality, and (e) Principal stress plane (FLSD).

An FLC has been created for the virgin material. FLCs have also been calculated after pre-straining in uniaxial tension, and equibiaxial tension, respectively, according to Fig. 2(a). The MFC failed to give reliable results for some strain paths as is evident from the figure. The reason for this has to be investigated further. The resulting three forming limit curves have then been plotted in four other variable spaces according to Fig. 2 (b)-(e). As can be seen there are perfect matches between the curves in all cases except (c). This case has been included in order to investigate what happens if plastic strain rates, which are the theoretically correct variables, are substituted by total strain rates. As is evident, this is not an acceptable approximation, maybe due to the extremely high stresses that may prevail in boron steel. The magnitude of the elastic strains may in such a case become significant. The present example has verified the expected path independency for an isotropic hardening material.

6.2 Results obtained with CrachFEM

Limit curves have been created by means of CrachFEM and „reversed engineering“. A single finite element has been subjected to various prescribed strain paths, and the strain and stresses have been recorded when CrachFEM indicates necking failure. Similar limit curves as in the case with the MFC have been constructed according to Fig. 3 (a)-(e). The most striking result from this exercise is that the curves do not match very well. A possible explanation to this difference compared to the MFC results could be that in the CrachFEM analyses kinematic hardening was assumed. It should be emphasized that the fact that the MFC results seemingly indicate path independency does not necessarily mean that the MFC provides more path independent results than CrachFEM in practice, since the assumption of isotropic hardening is an approximation in itself.

7 Material failure models in LS-DYNA

7.1 Introductory remarks

Several material models in LS-DYNA have in later years been supplemented with various fracture and

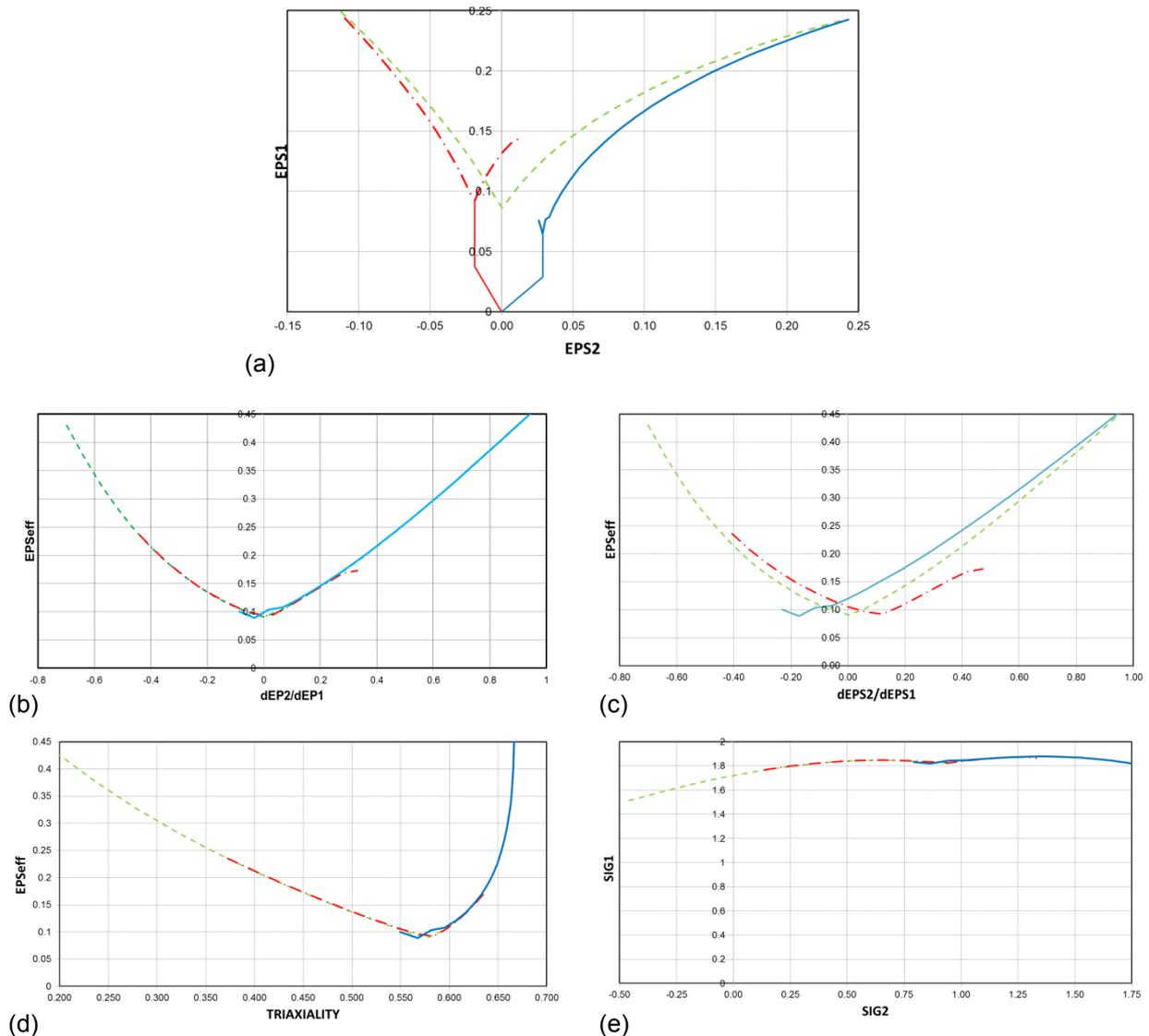


Fig.2: Forming limit curves obtained with the MFC. (a) FLD, (b) Effective strain vs principal plastic strain ratio, (c) Effective strain vs principal strain ratio, (d) Effective strain vs stress triaxiality, (e) FLSD

necking models. The *MAT_ADD_EROSION option does also provide the possibility to include failure and erosion options to arbitrary material models. It is the object of the current chapter to give a brief overview of the models that are available in LS-DYNA for necking risk evaluation.

7.2 MAT_190 - MAT_3-PARAMETER_BARLAT

The current material model is based on the Barlat-Lian yield criterion (YLD89). The model has been complemented with a failure criterion in the form of a traditional FLD. The limit curve is input as a load curve with tabulated data of minor and major principal engineering strains expressed in percent. A risk factor varying between 0 and 1, where the value 1 indicates failure, can be output. This failure risk for a strain state defined by the point $(\varepsilon_2, \varepsilon_1)$ in the principal strain plane is defined by

$$risk = \frac{\varepsilon_1}{\varepsilon_1^*} \quad (2)$$

where ε_1^* is the limit major strain corresponding to the minor strain ε_2 . The current model is obviously *not* path independent. It is still amazing how useful a simple model like this can be. After all, most strain paths in both sheet forming operations and in automobile structures subjected to impact loads are relatively linear. In such cases the current method is good enough. It should finally be added that the current model does allow for element erosion when the failure strain is reached.

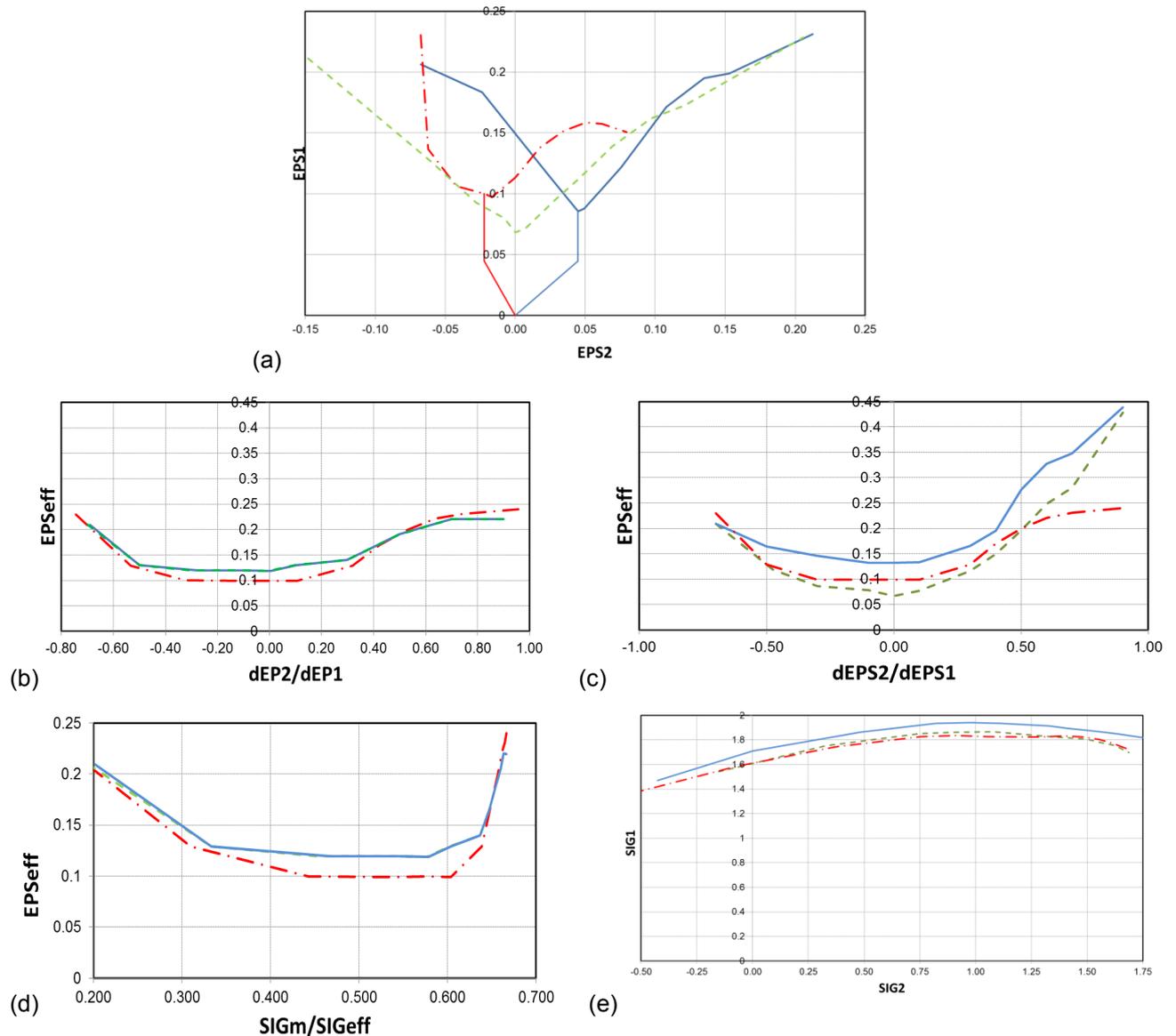


Fig.3: Forming limit curves obtained with CrachFEM. (a) FLD, (b) Effective strain vs principal plastic strain ratio, (c) Effective strain vs principal strain ratio, (d) Effective strain vs stress triaxiality, (e) FLSD

7.3 MAT_036 - MAT_3-PARAMETER_BARLAT_NLP

Like MAT_190 this model is based on the Barlat-Lian yield condition, and allows for kinematic hardening. A path independent necking criterion can be activated. The input to the failure model is a traditional FLC expressed in logarithmic strains. Internally, however, the failure algorithm works in an effective strain/principal plastic strain ratio plane. This is, thus, the model discussed in Sect. 2.4 and in Refs. [7] and [8]. In this model a „failure index“ (F.I.) can be calculated according to

$$F.I. = \frac{\bar{\varepsilon}^p}{\bar{\varepsilon}^{p*}} \quad (3)$$

where $\bar{\varepsilon}^{p*}$ is the limit effective plastic strain corresponding to the current ratio $d\varepsilon_2^p/d\varepsilon_1^p$. Erosion of failed elements is not possible in the current model.

7.4 MAT_037 - MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC_NLP_FAILUREMAT

MAT_037 reminds very much of MAT_036 above. The main difference is that the current material model is based on the transversely anisotropic version of the Hill'48 yield condition. The path independent failure evaluation is identical to the previous model.

7.5 MAT_ADD_EROSION

The MAT_ADD_EROSION option makes it possible to link one or more separate failure criteria to basically any material model. Erosion of elements that have satisfied a failure criterion is possible. Within the MAT_ADD_EROSION framework two failure models are available who show many similarities and offer great flexibility. These are the GISSMO and DIEM (Damage Initiation and Evolution Model) models. They can both handle ductile fracture and shear fracture with different kinds of damage models.

There are two options for instability prediction in DIEM named MSFLD and FLD, respectively. The input to both models is an FLC expressed in effective plastic limit strain $\bar{\epsilon}^{p*}$ as a function of principal plastic strain ratios α . Both these variables are, however, internally calculated as if the yield condition was a von Mises one, irrespective of the appearance of the real yield condition. This introduces a minor error whose magnitude depends how much the real yield surface deviates from the von Mises surface.

In the MSFLD model a failure risk factor ω_D is defined so that it takes the value 1 at incipient necking. This risk factor is calculated in the same way as the forming index in MAT_036 and MAT_037, with the exception that a modified effective strain is used, which is not accumulated when the material is in compression. The definition of this modified effective strain can have the negative consequence that the evolution of the risk factor can get discontinuous depending on the strain path.

In the new FLD model the risk factor is assumed to evolve in the same way as the damage initiation history variables in the ductile and shear criteria in DIEM. The evolution equation is defined as

$$\omega_D = \int_0^{\bar{\epsilon}^p} \frac{d\bar{\epsilon}^p}{d\bar{\epsilon}^{p*}(\alpha)} \quad (4)$$

It should be noted that, for a straight strain path, this model yields the same results as the other models discussed herein, and the risk factor gets the value 1 when the strain path hits the static FLC.

8 Results obtained with the failure models in LS-DYNA

8.1 Introductory remarks

Finally, results from four of the models discussed will be compared. These are: MAT_190, MAT_037, DIEM_FLD, and CrachFEM. Of these MAT_190 is path dependent, while the other three models exhibit some kind of path independency. It should be emphasized that there do not exist any “correct answers” in these comparisons. All models involve different kinds of approximations. The results can only give an indication on how serious the path dependency effect is, and whether the trends of the results from the different models point in the same direction.

8.2 Results and comments

A single finite element has been subjected to three different strain paths according to Fig. 4. The first striking observation is how large the path dependency effect is. The second observation is that there are differences in the results from the three “path independent” models, but the trends are similar. It is at this time impossible to say which method is the most correct one.

9 Summary and conclusions

Experiences from sheet forming and automobile crash simulations have revealed that strain localization (necking) in the vast majority of cases precedes any type of fracture. Plastic instability is therefore in most cases the most dangerous failure mode. This is true even for ultra high strength steel with low ductility. In the sheet forming community it is still common practise to evaluate the risk for necking by means of a static Forming Limit Curve (FLC) in the principal strain plane. The main disadvantage of this concept is that strain localization is highly strain path dependent, and that a static FLC is not applicable in cases with highly nonlinear or broken strain paths.

In the current paper a few different concepts for strain path independent necking failure risk evaluation are discussed. Especially the models available in LS-DYNA are reviewed. Applications of a few of the models to an example with broken strain paths have revealed that the path dependency effect can be surprisingly strong. The results from the different models differs somewhat, but the trends are the same.

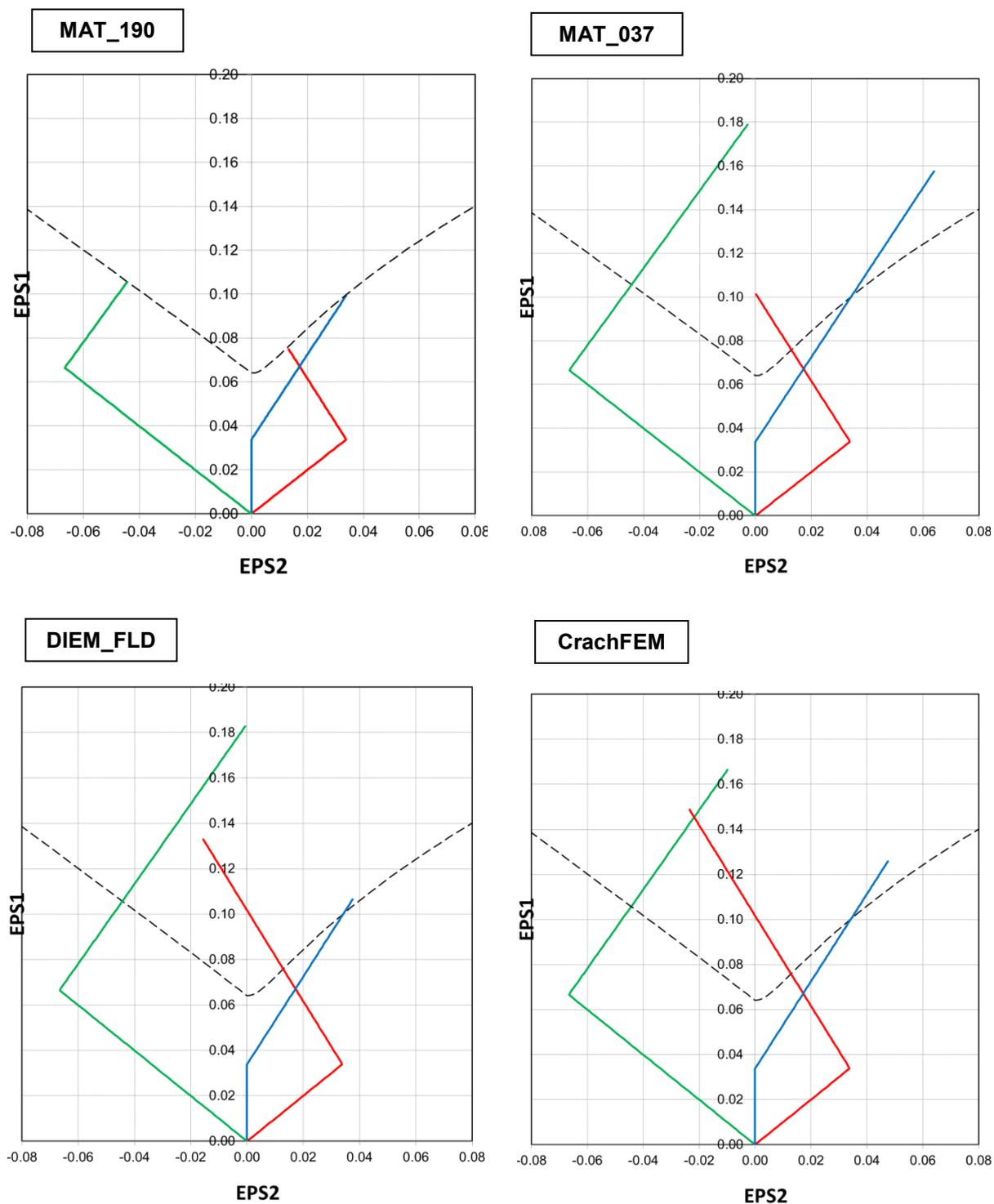


Fig. 4: A single finite element subjected to three different broken strain paths. Necking predicted with four different failure models.

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