ENHANCED FAILURE PREDICTION IN SHEET METAL FORMING SIMULATIONS THROUGH COUPLING OF LS-DYNA AND ALGORITHM CRACH

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Abstract

In sheet-metal-forming the forming limit curve (FLC) is used for ductile sheets to predict fracture in deep drawing. However the use of the FLC is limited to linear strain paths. The initial FLC cannot be used in a complex nonlinear strain history of a deep drawing process or a successive stamp and crash process including a significant change in strain rate. The CRACH software has been developed to predict the forming limit of sheets for nonlinear strain paths [1]. It has been validated to predict instability for bilinear strain paths with static loading in the first path and dynamic loading in the second path for mild steels [2].

As the postprocessing of strain paths from single finite elements in CRACH is not economic for industrial applications MATFEM initiated a project to couple CRACH directly with FEM-Code LS-DYNA using a user-defined material model. This allows a prediction of possible failure during the simulation for all elements with respect to their complete strain history. A special strategy has been developed to include CRACH without extensive increase in total CPU time. The developed interface to LS-DYNA allows also the implementation of other failure criteria demanding the history of deformation like for example a tensorial fracture criterion.

In order to test the reliability of the calculated safety factor experimental tests for bilinear strain paths have been simulated [2]. In this case the experimental and numerical investigations have been made on two-stage forming processes (static in the 1st stage and both static/dynamic in the 2nd stage) . The static-static case should simulate a stamping process with bilinear strain path. The static-dynamic case should simulate a successive stamp and crash process.

The simulation of a complex deep drawing problem including areas with significantly nonlinear strain paths has been simulated with LS-DYNA/CRACH-coupling. It can be shown that the prediction of CRACH can differ significantely from a “standard” prediction based on the initial FLC.

The coupling of LS-DYNA and CRACH showed the potential to predict possible fracture in deep drawing and crash loading at an early design stage and allowed to optimise geometry and material quality to significantly reduce later problems in real components.

Introduction

As the validation of the method has already been carried out for even complex deformation histories of deep drawing with successive crash loading, this work is focused on the coupling of algorithm CRACH with LS-DYNA through a user defined material model. In this case an orthotropic yield locus according to Hill-1948 [5] is used. For the calculations in LS-DYNA the yield locus is combined with an isotropic hardening model. A mixed isotropic-kinematic hardening model is used in CRACH algorithm to account for the Bauschinger effect in cases of nonlinear strain paths. In order to ensure the possibility to adapt CRACH to the behaviour of different materials, other formulations of the yield locus can be used. As an example the simulation of a complex drawing part with element refinement is shown to demonstrate the difference between the calculated safety-factor against the initial forming limit curve and the enhanced failure prediction considering the forming-limit curve after nonlinear strain paths. Further industrial applications are discussed.

Approach

Instability and Fracture

The in-plane deformation of ductile sheet structures leads to local instability as one main failure mechanism when hardening of the material is not able to retard the process of necking. At this point strain localizes in the necked area and leads to fracture with negligible increase in macroscopic deformation. So as shown in figure 1 the global instability strain φ_1* can be used in practical application as a fracture criterion instead of considering the local fracture strain φ_1**.

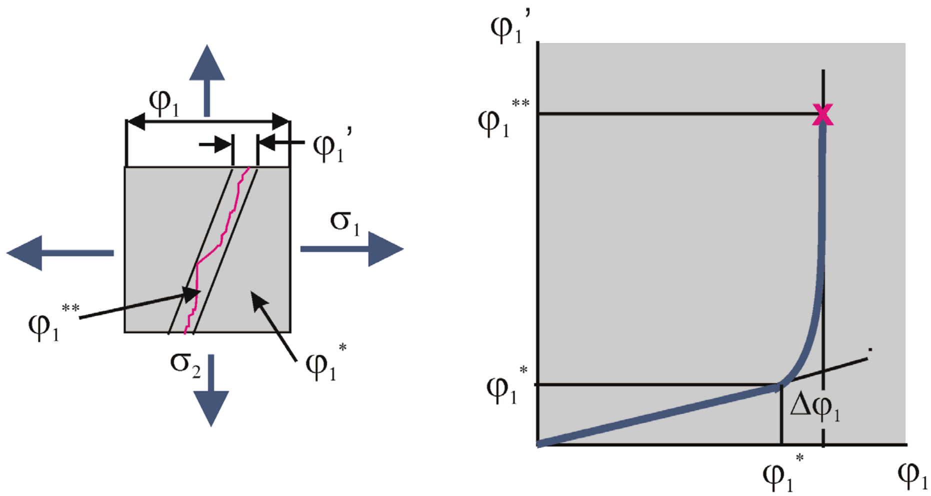
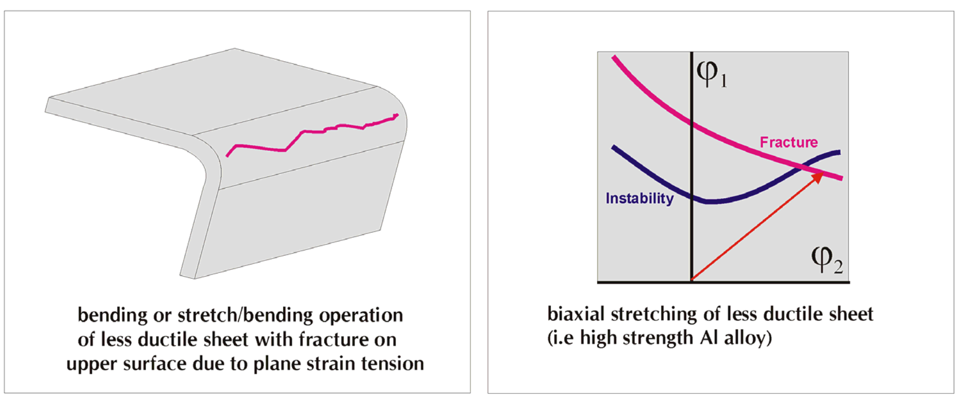


Figure 1: Global instability strain and local fracture strain

However there are also cases of fracture without instability for less ductile sheets (i.e. high strength aluminium sheets). In this case the fracture strain (red curve in Figure 2b) is shifted to lower strains and crosses the instability curve in the region of biaxial stretching. Additionally in stretch-bending operations with small radii (Figure 2a) fracture can be initiated at the outer surface of the sheet. There is no instability as the membrane strain is zero (pure bending) or small (stretch-bending). For these cases one need to have also fracture criteria besides the FLC.



a) b)

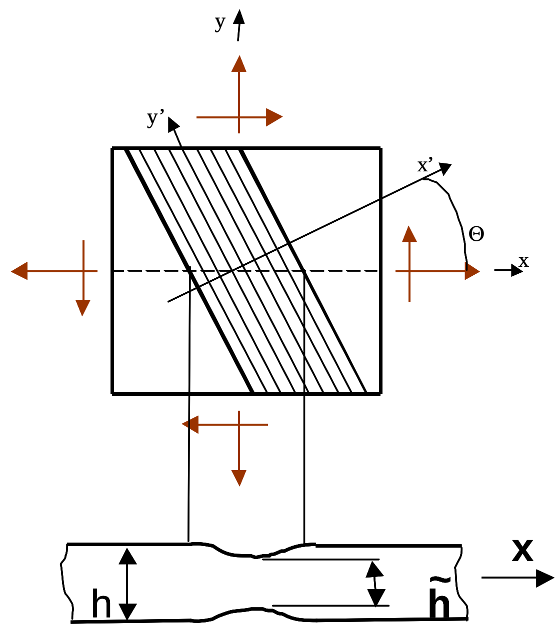
Figure 2: a) Bending or stretch-bending operation of less ductile sheet with fracture on upper surface due to plane strain tension; b) fracture before instability in case of biaxial stretching of less ductile sheet (i.e. high strength Al alloy)

Mechanical model describing the Instability in Algorithm CRACH

CRACH is searching for a solution of the plastic deformation (necking) of a thin sheet assuming an initial imperfection as show in Figure 3. The mechanical model is based on the following characteristics:

1. orthotropic plasticity;
2. isotrop-kinematic hardening model (Bauschinger effect);
3. model for strain rate dependency;
4. use of a inhomogenity-parameter for calibrating the quality of the sheet-charge (forming limit strain of one linear strain path is necessary)

5. realistic approximation for the geometry of the local necking (orientation of localized necking is rotated to find weakest orientation);
6. material parameters can change between successive processes (heat treatment between forming steps; change in strain-rate in crash after deep-drawing.



$$d = (h - \tilde{h}) / h$$

Figure 3. Model of initial necking in CRACH

For nonlinear strain paths the Bauschinger effect has an important influence on the forming limit curve. Therefore CRACH uses a combined isotropic-kinematic hardening model. Figure 4 shows the influence on a simple two-stage forming process (the forming limit is also strongly influenced by a continuously varying strain path like in drawing processes.)

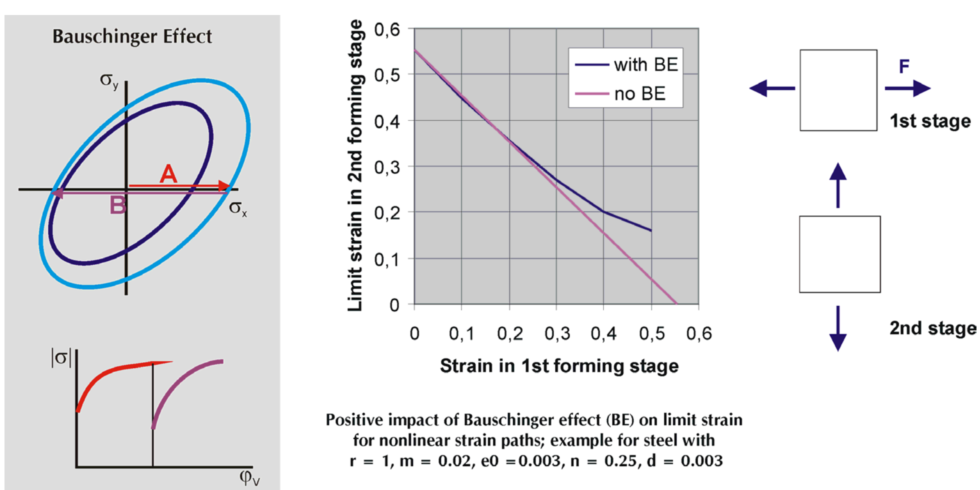


Figure 4. Influence of the kinematic hardening on the forming-limit in a bilinear 2-stage forming process

As input parameters CRACH needs the strain-rate dependent hardening curve, the plastic anisotropy (r-values) and one experimental value on the initial forming limit curve – for example one from uniaxial tension – for calibration of the inhomogenity parameter.

The algorithm CRACH has been introduced by MATFEM first through the PC/WINDOWS software CRACH/LAB for:

- calculation of initial FLC,
- calculation of remaining FLC after prestraining,
- calculation of safety factor against sheet instability for non-linear strain paths

with interfaces

- to import and approximate flow stress curves,
- to import strain histories from single finite elements for postprocessing.

CRACH/LAB is actually used at steel and aluminium sheet producers to study the influence of plastic properties on the forming limit curve.

The algorithm to calculate the safety factor against sheet instability for non-linear strain paths has been used for the coupling with the FEM code LS-DYNA.

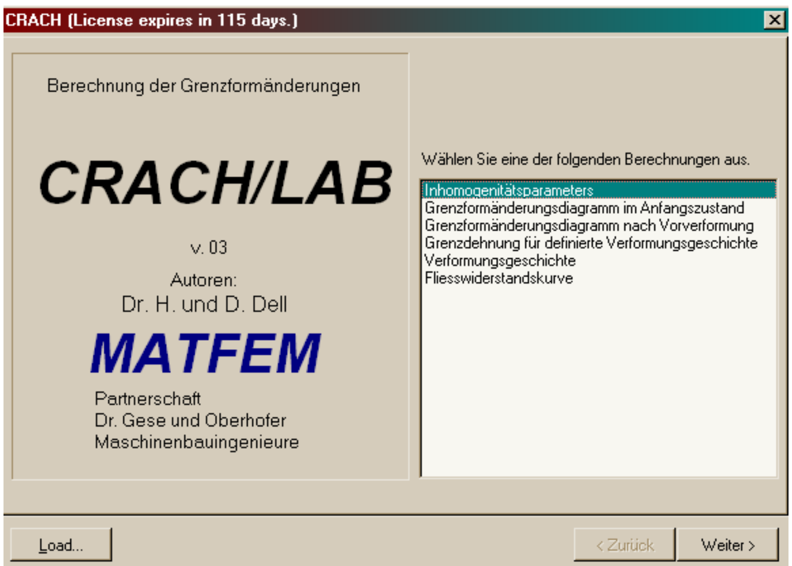


Figure 5. PC/Windows-Software CRACH/LAB for calculation of forming limit curves with and without prestraining

Mechanical model describing Fracture

In order to grasp the problem of failure as a whole the mechanism of fracture has to be considered additionally to instability. Therefore detailed investigations have been carried out by MATFEM. As this paper is focused on the description of instability, fracture is not discussed in detail although the algorithm is able to handle the calculation of a safety factor against fracture. In case of fracture the material damage is described in tensorial form [1]. Two fracture mechanisms – ductile fracture and shear-fracture - are distinguished. In case of ductile fracture the fracture plane is perpendicular to the largest tensile stress and for shear fracture the fracture-plane is the plane of the largest shear stress. It is assumed that in case of ductile fracture the deformation at fracture is a function of the stress-triaxiality.

Validation

Figure 6 shows a comparison of experiments by Müschenborn und Sonne [6] and calculated results by "CRACH" for the residual FLC after uniaxial (φ_1=0.2) and equibiaxial (φ_1=0.1) prestraining. In this example the material is transversal isotropic steel with r=1.36, n=0.203, m=0.02 and d=0.013 (from $\varphi_1{}^*_{exp}$)

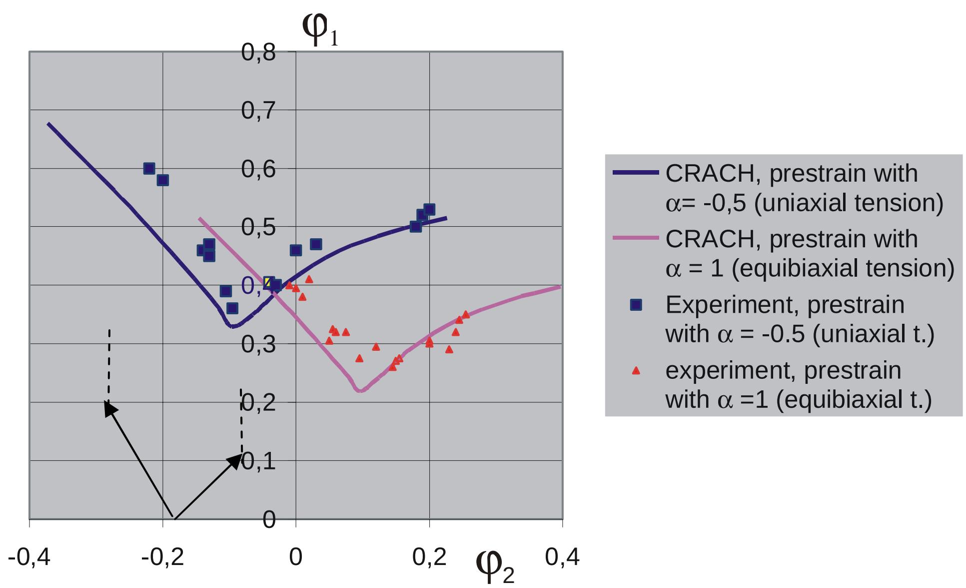


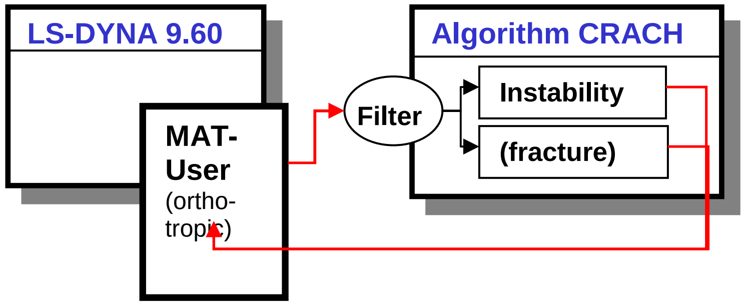
Figure 6. Comparison of experiments by Müschenborn und Sonne [6] and calculated results by CRACH/LAB

This example shows the influence of pre-straining and the correlation between experimental results and the analytical calculated forming limit curve with algorithm CRACH.

In order to test the reliability of the calculated safety factor experimental tests for bilinear strain paths as described in [2] have been simulated. In this case the experimental and numerical investigations have been made on two-stage forming processes. In reality the first of these two stages reflects a stamping process, followed by a second stage stamping process. This second stage could also be a crash process.

Implementation of Algorithm CRACH in LS-DYNA 9.60

The coupling of Algorithm CRACH with LS-DYNA was carried out through the user-material-interface. An orthotropic user-material model has been used to characterize sheet materials. Stress and incremental strain-tensor are transferred to a submodule for filtering the input data used in algorithm CRACH. Additionally the CRACH related material parameters, integration-point history variables and element-information are transferred to the CRACH-Module. Figure 7 shows the interfacing of the submoduls.



Postprocessing of safety-factor "SF"against instability and fracture with LS-POST V 2.0 Beta. Failure if SF<1.0

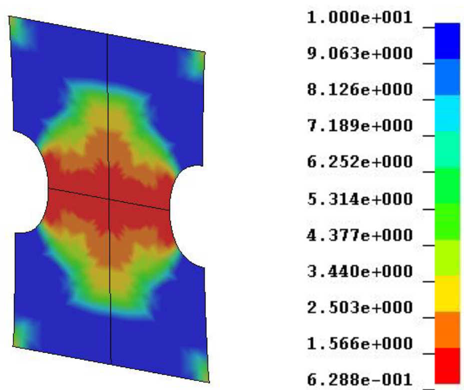


Figure 7. Coupling of LS-DYNA 9.60 with algorithm CRACH

A special strategy has been developed to include CRACH without extensive increase in total CPU time. The calculation of the safety factor against instability will be updated if the equivalent plastic strain in one element has been increased by 3%. For safety factors greater than 2.0 a simplified calculation against the initial FLC is performed. If the calculated value falls below 2.0 an advanced calculation with respect to the non-linear strain history with algorithm CRACH is started. In Table 1 the increase of CPU-time using algorithm CRACH for calculation of a complex deep-drawing part described later on is compared.

Table 1. Comparison of required CPU time used to simulate a drawing problem

	CPU time	Increase in %
User-Mat (Hill-48) without calculation of safety factors	8h 10min 18sec	-
User –Mat (Hill-48) with calculation of safety factor against initial FLC, ductile fracture and shear fracture	9h 13min 33sec	12,9
User-Mat (Hill-48) with calculation of safety factor against instability dynamically with CRACH with respect to the nonlinear strain history, ductile fracture and shear fracture	9h 52min 28sec	20,8

In the present version of the interface LS-DYNA can be used with CRACH for continuously varying load paths like for example in deep-drawing processes. At the moment there is no option for the division of the load history into several substeps with discontinuous changes of deformation path or changing CRACH–parameters. As algorithm CRACH is designed to handle this cases additional work will be focused on the development of the submodul FILTER. The restriction includes also the mapping of CRACH parameters between different FEM meshes used for simulating deep drawing with successive crash loading with different FEM-meshes. Therefore the CRACH parameters describing the strain history have to be mapped additionally.

Simulation

The following investigation concentrates on the prediction of instability calculated by algorithm CRACH.

Simulation of 1-element examples

In order to test the evaluation of the safety-factor with algorithm CRACH some simple 1-element-tests described in Figure 8 were carried out assuming orthotropic material behaviour.

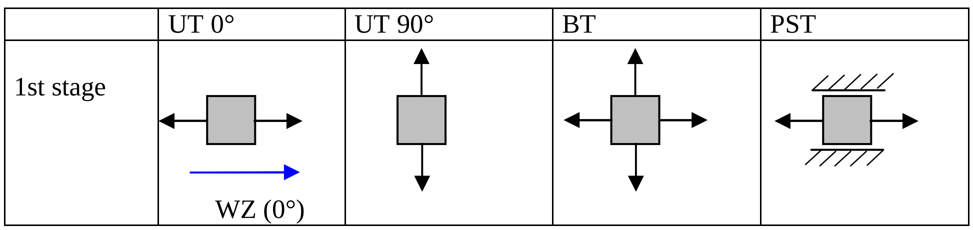


Figure 8. 1-element-tests

Figure 9 shows the safety-factor versus the equivalent plastic strain. The equivalent plastic strain where the safety-factor reaches the value 1.0 are points on the initial forming limit curve (UT=uniaxial tension, BT=biaxial tension, PST=plane strain tension).

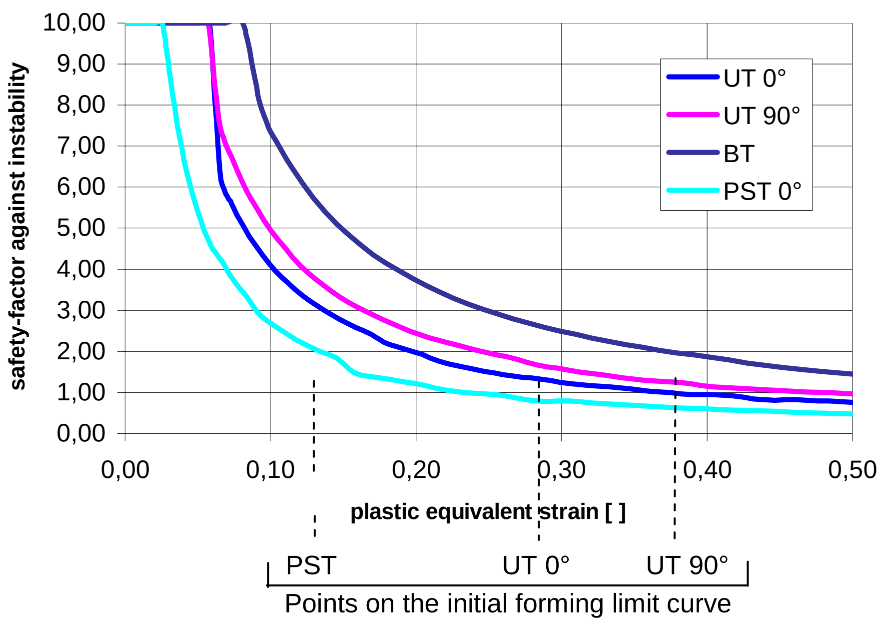


Figure 9. Safety-factor versus equivalent plastic strain showing the influence of FLC orthotropy

The calculation of the safety-factor against FLC is not unique. One convenient way is to use the forming limit at the value of ε_2 as shown in figure 10a. This assumes a constant ε_2 (plane strain) for the succeeding deformation path. A more suitable definition for a technological process is to describe the FLC in coordinates of the equivalent plastic strain ε_v versus the ratio of ε_2 and ε_1, α, described in figure 10b. The safety-factor against instability is calculated from the ratio of the equivalent plastic strain to the corresponding forming limit strain. In this case the ratio of ε_2 and ε_1 is held constant (i.e. the loading path is extrapolated continuously with the same type of loading as at the end of the forming process)

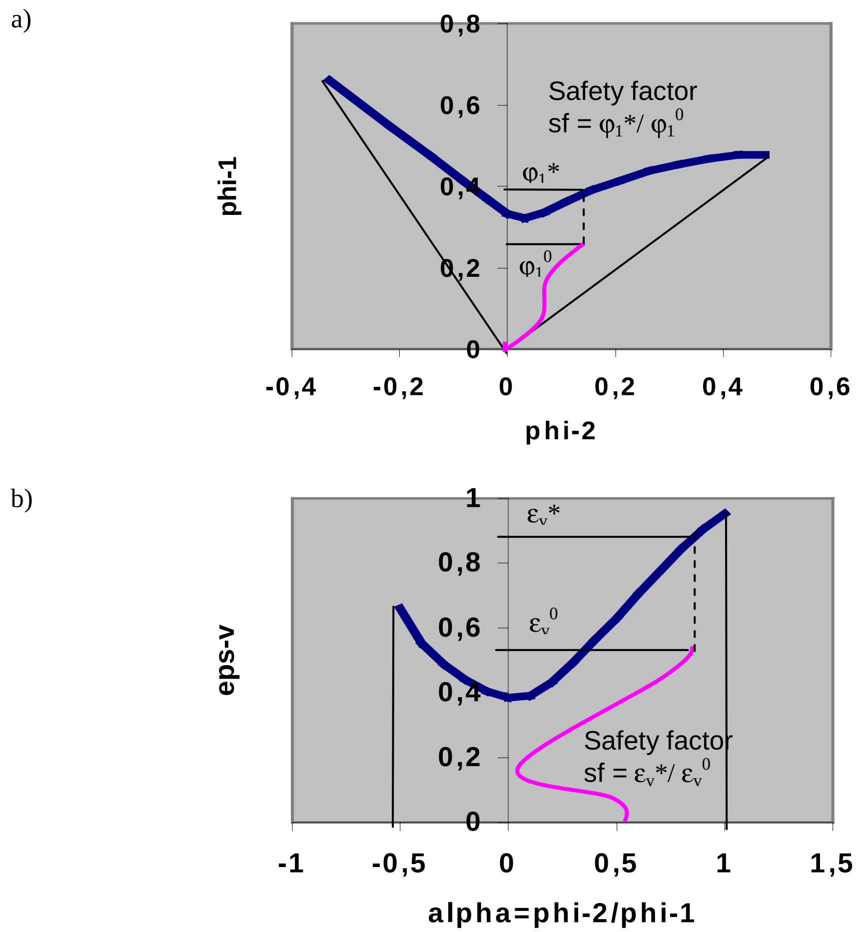


Figure 10. Definitions for the calculation of the safety factor against instability – (a) conventional definition (b) definition used in CRACH

Simulation of a complex deep-drawing problem

The initial forming limit curve is the basis for calculating the safety-factor against instability in industrial applications today. In order to show the enhancements in predicting of the safety-factor against instability using algorithm CRACH, simulations of a complex deep-drawing process with element refinement are performed. First the calculations were made using the initial FLC and in a second calculation the FLC with respect to the non-linear strain path calculated with CRACH is considered. In both cases a definition of the safety factor according to Figure 10b is used. In this example the sheet material is mild steel. Ductile fracture (before instability) and shear fracture will not occure for this extremely ductile material. The deformation is only limited by the instability curve. Figure 11 shows the geometry of the test example – a drawing part from [4].

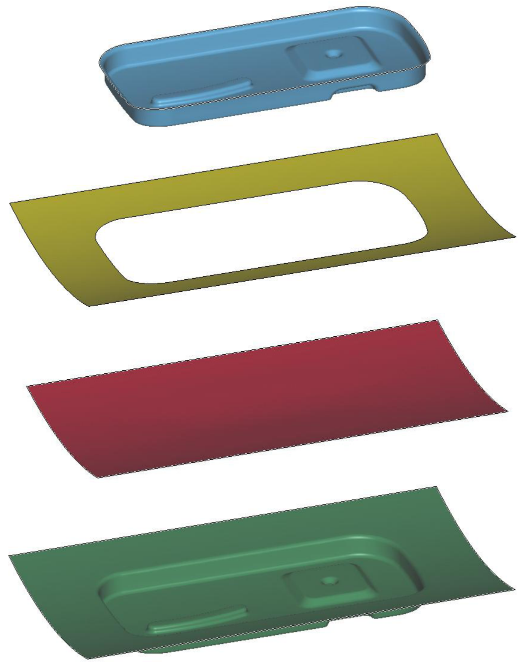


Figure 11. Geometry of punch, blankholder, sheet and die of the drawing part [4]

In figure 12 the overall distribution of the safety-factor against instability given by CRACH is shown at 100% stroke. Values less than 1.0 (red) indicate fracture.

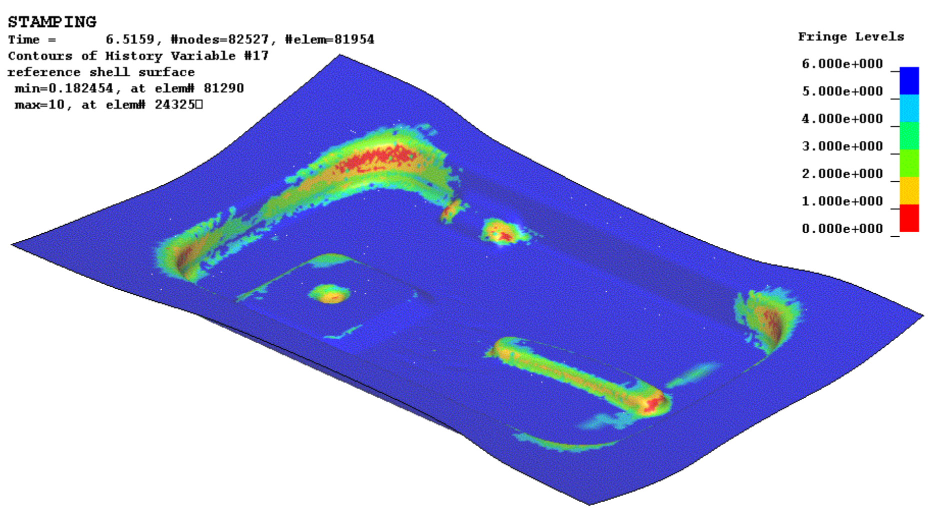


Figure 12. Overall distribution of the safety-factor against instability given by CRACH (non-linear strain-history is considered)

In figure 13 and 14 the safety-factor against instability using the initial FLC (figure 13) and the the dynamically calculated FLC (CRACH) (figure 14) is compared after 56% stroke for one corner of the drawn part.

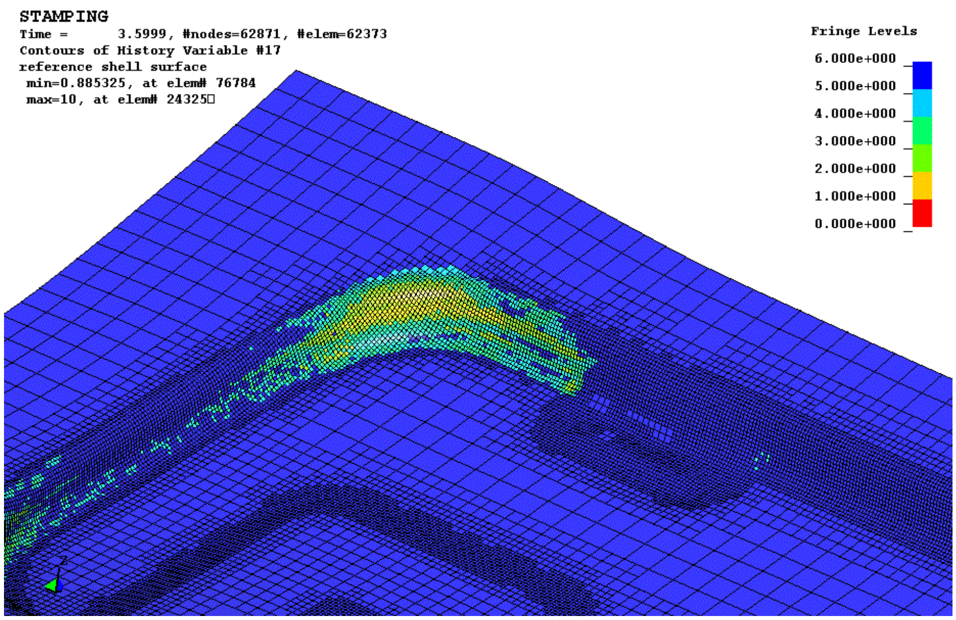


Figure 13. Safety-factor against instability with respect to an initial forming limit. (non-linear strain-history is not considered)

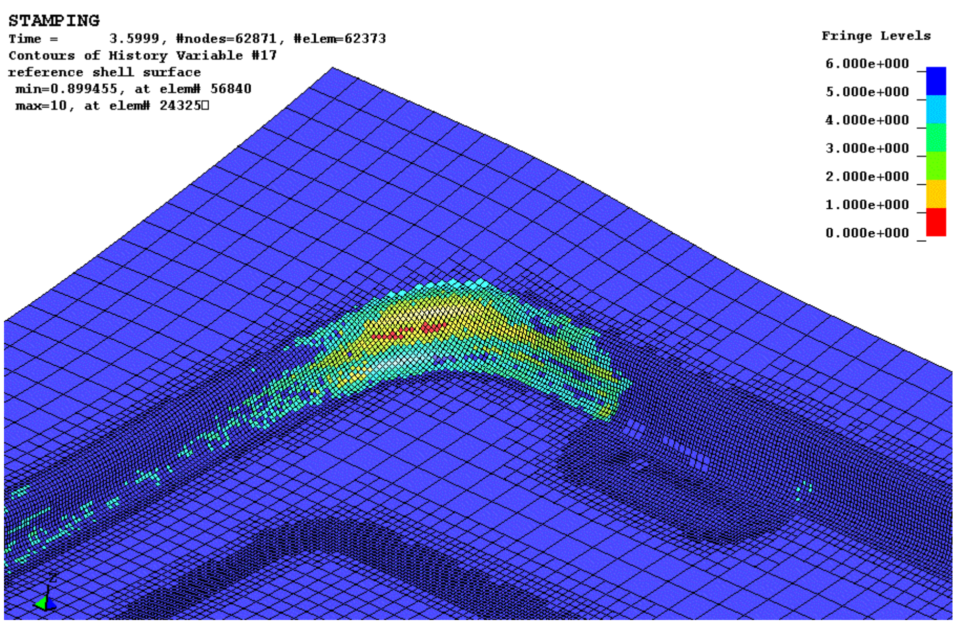


Figure 14. Safety-factor against instability with respect to the calculated forming limit. (non-linear strain-history is considered)

Discussion of Results

For comparison one critical region with a nonlinear strain path shown in figure 13 and figure 14 is considered. In Table 2 the percentage of stroke when the safety-factor falls under a critical value of 1.0 is compared for the two methods.

Table 2. Stroke when safety-factor against instability falls under the critical value of 1.0

	Initial FLC	FLC calculated dynamically with CRACH with respect to the nonlinear strain history
Stroke [mm]	41	30
Percentage of complete stroke [%]	76	56

In this case the forming-limit with respect to the non-linear strain history is reached after 56% stroke, 26% before the forming limit is reached assuming initial forming limit. This example shows the importance of taking into account the complete history of the deformation process.

Conclusion

In sheet-metal-forming- and crash-simulation two mechanism of failure – instability and fracture- have to be considered. The use of the initial forming-limit-curve (FLC) for instability is limited to linear strain paths. This FLC cannot be used in a complex non-linear strain history. With algorithm CRACH the FLC can be calculated even for a complex strain history resulting from deep-drawing processes or deep drawing processes with successive crash process. In some cases fracture which can be divided into ductile-fracture and shear-fracture can occur before instability. An additional algorithm which was not discussed in detail in this paper handles the calculation of a safety-factor against fracture.

As the postprocessing of a single strain paths from LS-DYNA in CRACH is not economic for industrial applications MATFEM initiated a project to couple CRACH directly with LS-DYNA using a user-defined material model. With a special strategy the increase in CPU-time has been reduced to approximately 20% for an example drawing problem compared with a solution without calculation of a safety factor against instability and fracture. The coupling of LS-DYNA and algorithm CRACH has the potential to predict possible fracture in deep drawing and crash loading at an early design stage and allows to optimise geometry and material quality to significantly reduce later problems in real components.

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