# Forming and Crash Induced Damage Evolution and Failure Prediction Part 1: Extension of the Gurson Model to forming Simulations

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**Abstract:**

With increasing requirements on the crash safety of automotive components and on virtual prototyping it is important to model the damage and the failure behaviour of structural components in crashworthiness simulations. In the past several continuum models have been developed to simulate the ductile damage behaviour of metals. Among these models the Gurson constitutive model has been applied successfully in crash simulations. Usually ductile damage models assume either initial damage equal to zero or a constant value very close to zero at the beginning of the crash simulation. Generally these models do not take into consideration that damage already evolutes from the metal forming process. Therefore in the present work the damage description of the micromechanically motivated Gurson model has been linked to the Barlat model, which is a widely used material model for sheet metal forming processes. It will be shown that prediction of the damage in metal forming processes and subsequently the use of the results as initial damage values in crash simulations is possible and necessary to predict structural failure in crashworthiness simulations.

**Keywords:**

Process Chain, Damage Models, Sheet Metal Forming, Crash Simulation

# 1 Introduction

Although crash simulations have been successfully used for development of automotive structures (i.e. bodies in white), the automobile industry has the ambition to steadily improve the accuracy of its simulations. One improvement could be the modelling of damage evolution in automobile components under crash loading. However the damage behaviour of forming processes is not taken into account although damage (i.e. deterioration of elastic parameters) already occurs under forming loading. The non-consideration of this fact leads to an overestimation of the load-carrying capacity and the absorbed energy of structural components. A description of the damage evolution in forming processes would result in a maximum utilisation of the materials and sections used and therefore to a considerable reduction of weight.

The purpose of this work is to characterize and implement a damage evolution into a widely used forming material model. Hereby the damage evolution should be implemented in a manner which leaves the forming material model unaltered. The aim is to get additional information for the damage variable by running the Gurson model parallel in the background of the foreground Barlat model. Therefore the damage evolution needs to be adjusted for pressure-independent material models like the Barlat model. This will be described in the following sections. The Implementation will subsequently be verified on small simulation models and validated on structural components.

# 2 Damage Model

Various continuum models have been developed for modelling ductile damage behaviour of metals. All of them have a strong dependence of the damage development on the stress triaxialty. One successful concept is the micromechanical Gurson model in which the ductile failure process is described by nucleation, growth and coalescence of microvoids. The advantage of the Gurson model is its micromechanical motivated description and the possible physical interpretation of the damage parameter [2].

## 2.1 Gurson model

The Gurson model modified by Tvergaard and Needleman [1] uses the yield condition

$$\Phi = \frac{q^2}{\sigma_M^2} + 2q_1 f^* \cosh\left(\frac{-3q_2 p}{2\sigma_M}\right) - 1 - (q_1 f^*)^2 = 0 \qquad (1)$$

Here $\sigma_M$ denotes the actual yield stress of the matrix material, $q$ the equivalent von Mises stress, $-p$ the hydrostatic mean stress and $f^*$ the effective void volume fraction given by

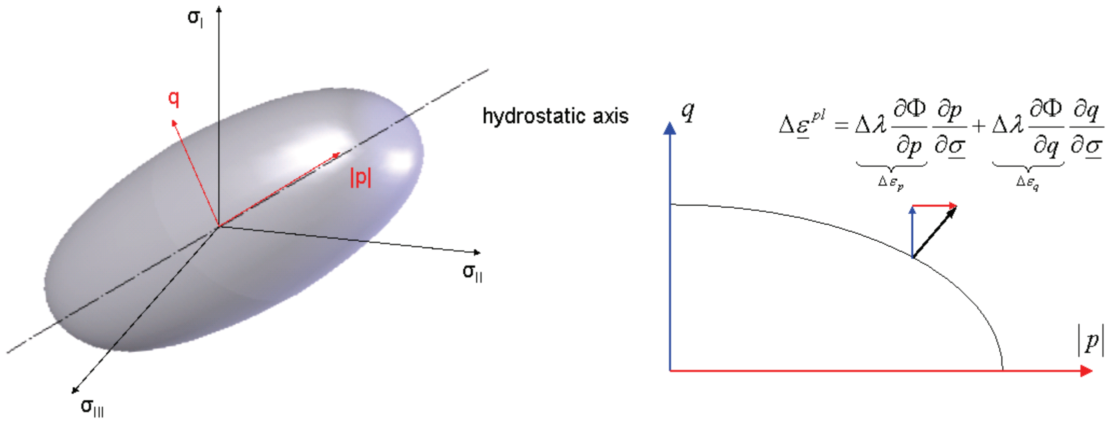
$$f^*(f) = \begin{cases} f & if \quad f \le f_c \\ f_c + \dfrac{1/q_1 - f_c}{f_f - f_c}\left(f - f_c\right) & if \quad f > f_c \end{cases} \qquad (2)$$

Where f is the void volume fraction, $f_c$ and $f_f$ are the critical void volume fraction at onset of coalescence and at final rupture, respectively. The evolution equation for the porosity consists of the growth of existing voids and nucleation of new voids:

$$\Delta f = (1-f)\Delta\varepsilon_p^{pl} + A\Delta\varepsilon_M^{pl} \quad , \quad A = \frac{f_N}{s_N\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_M^{pl} - \varepsilon_N}{s_N\sqrt{2\pi}}\right)^2} \qquad (3)$$

where $\Delta\varepsilon_p^{pl}$ is the hydrostatic part of the plastic strain increment and $\Delta\varepsilon_M^{pl}$ the microscopic plastic strain increment of the matrix. The advantage of the Gurson model is the micromechanical motivation and the physical meaning of the damage parameters as porosity. The Gurson model exhibits strain softening and therefore the individual parameters that define the softening branch are subject to strain localization and therefore yield mesh size dependent results. This can be circumvented by defining and calibrating individual sets of parameter based on the actually applied element size. Hence it is possible to obtain mesh independent results.

#### *2.1.1 Gurson Yield surface and Plastic Potential (F=Q)*




*a)* *b)*

*Figure 1: a) Partially damaged yield surface of the Gurson model in principal stress space*
*b) Plastic potential in the meridional plane*

Final failure of a porous ductile solid occurs by void coalescence. According to the Gurson model, loss of stress carrying capacity occurs when the voids have grown so large that the yield surface (1) has shrunk to a point.

A limitation of the Gurson model for metal forming simulations as well as crash simulations is that it is not able to describe shear-dominated failure. A possible concept which is used in crash simulation is the utilization of an additional failure model. Here the Johnson-Cook criterion [6] is applied to account for shear dominant loading, while the standard Gurson damage behaviour is used to trigger failure between uniaxial and biaxial tension.

## 3 Metal forming process

Sheet metals are usually orthotropic due to the rolling pre-treatment. Material models used for metal forming processes are therefore able to describe anisotropic behaviour. Most of the anisotropic material models assume hereby pressure independence, i.e. the formulation is isochoric. This assumption is acceptable as long as materials do not exhibit high porosity. One successful orthotropic material model is the model of Barlat (MAT_36 LS-DYNA).

### 3.1 Barlat model

The anisotropic yield criterion for plane stress is defined as:

$$\Phi = a\left|K_1 + K_2\right|^M + a\left|K_1 - K_2\right|^M + c\left|2K_2\right|^M = 2\sigma_y^M \qquad (4)$$

Where $\sigma_y$ is the yield stress and $K_1$ and $K_2$ are given by:

$$K_1 = \frac{\sigma_x + h\sigma_y}{2}$$
$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2} \tag{5}$$

and a, c, h and p are anisotropy parameters which can be determined from the R-values. The yield function of Barlat reduces to the isotropic case when the constant coefficients a, c, h and p are all equal to 1 and furthermore to the vonMises yield function for M = 2 [3]. For the isotropic case the yield function is associated to the flow rule and therefore equal to the plastic potential (F=Q) as visualized in Figure 2.

### *3.1.1 Barlat Yield surface and Plastic Potential for the isotropic case (M=2)*

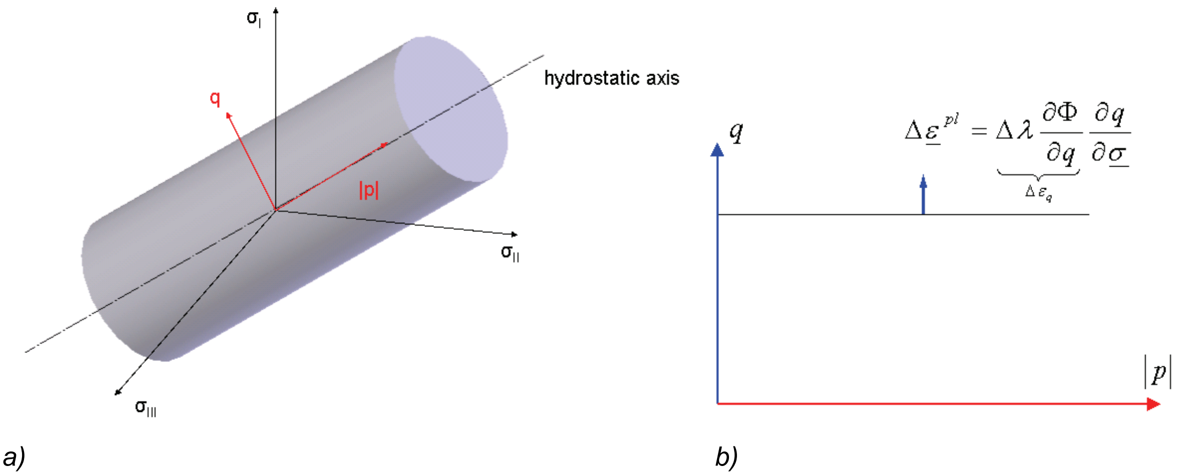



*Figure 2: a) Yield surface of the Barlat model in main stress space*
*b) Plastic potential in the meridional plane*

As shown in Figure 2b the Barlat model assumes incompressibility and therefore no volume change during plastic loading takes place. The hydrostatic component of the effective plastic strain, which accounts for the void growth in the damage evolution of the Gurson model, is zero.

## 4 Comparison of the two material models

The two different material models discussed in this paper have been presented in the previous chapters. In this section it is demonstrated that the two models lead to different results even if the parameters and flow curve definitions are chosen identical. This is exemplified on a small simulation that will be conducted with special interest in the plastic Poisson's ratio of the two models. Here the plastic Poisson's ratio is defined as:

$$\nu_p = -\frac{\varepsilon_{p,yy}}{\varepsilon_{p,xx}} \tag{6}$$

The simulation was performed by using both the Barlat and the Gurson model. A plastic ratio of 0.5 designates completely plastic flow behaviour leading to a constant volume during plastic loading. It can be seen from Figure 3 that the plastic Poisson's ratio value of the Barlat model is constant 0.5. However the plastic ratio of the Gurson model decreases with increasing displacement due to volume change.

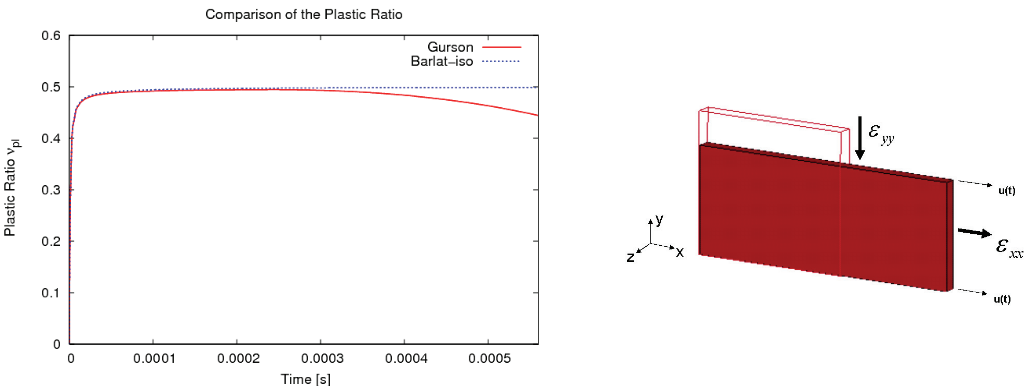


*Figure 3: Plastic ratio for two material models*

## 5 Characterisation of the damage evolution in the Barlat model

In the previous section the isochoric character of the Barlat model has been pointed out. Hence the damage evolution as formulated in the Gurson model, i.e. based on hydrostatic loading, may not be applied straight forward. However, the Gurson damage evolution in incremental form may be written as

$$\Delta f = (1-f)\Delta\varepsilon_p + A\Delta\varepsilon_q \quad , \quad A = \frac{f_N}{s_N\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_q-\varepsilon_N}{s_N\sqrt{2\pi}}\right)^2} \tag{7}$$

Here $\Delta\varepsilon_p$ is the hydrostatic part of the plastic strain increment, which is not available in the Barlat Model, and $\Delta\varepsilon_q$ is the macroscopic equivalent plastic strain increment which may be placed here instead of the microscopic plastic strain $\Delta\varepsilon_q^M$ with minor effect.

### 5.1 Determination of the hydrostatic effective strain

The hydrostatic effective strain may be computed using the flow rule and the compatibility equation. The associated flow rule is generally given as:

$$\Delta\varepsilon_{ij}^p = \Delta\lambda \frac{\partial\Phi}{\partial\sigma_{ij}} \tag{8}$$

Separated in a hydrostatic and a deviatoric part the flow rule yields:

$$\left.\begin{aligned} \Delta\varepsilon_{kk}^p &= \Delta\varepsilon_p = \Delta\lambda\frac{\partial\Phi}{\partial p} \\ \Delta e_{eq}^p &= \Delta\varepsilon_q = \Delta\lambda\frac{\partial\Phi}{\partial q} \end{aligned}\right\} \Delta\varepsilon_p\frac{\partial\Phi}{\partial q} + \Delta\varepsilon_q\frac{\partial\Phi}{\partial p} = 0 \longrightarrow \Delta\varepsilon_p = -\Delta\varepsilon_q\frac{\frac{\partial\Phi}{\partial p}}{\frac{\partial\Phi}{\partial q}} \tag{9}$$

Using the derivates of the yield function in (1)

$$\begin{aligned} \frac{\partial\Phi}{\partial p} &= \frac{-3q_2q_1f^*}{\sigma_M}\sinh\left(\frac{-3q_2p}{2\sigma_M}\right) \\ \frac{\partial\Phi}{\partial q} &= \frac{2q}{\sigma_M^2} \end{aligned} \tag{10}$$

the hydrostatic effective strain part can be finally described using (8) and (9):

$$\Delta\varepsilon_p = -\Delta\varepsilon_q \frac{-3q_2q_1\sigma_M f^*}{2q}\sinh\left(\frac{-3q_2p}{2\sigma_M}\right) \tag{11}$$

It is now possible to describe the damage evolution (7) in components which are available in the Barlat model. Thus the Gurson damage evolution may be written as:

$$\Delta f = (1-f)\frac{3q_2q_1\sigma_M f^*}{2q}\sinh\left(\frac{-3q_2p}{2\sigma_M}\right)\Delta\varepsilon_q + A\Delta\varepsilon_q \tag{12}$$

However this formulation does not take into account the fact that an increase of the damage parameter leads to a decrease of the load capacity. For this reason the plastic Poisson's ratio for tension was used to identify a correlation between the effective plastic strain increments in the Gurson and the Barlat model for the uniaxial case:

$$\nu_p = \frac{\frac{3}{2}\frac{\partial\Phi}{\partial q}+\frac{\partial\Phi}{\partial p}}{3\frac{\partial\Phi}{\partial q}-\frac{\partial\Phi}{\partial p}} = \frac{\frac{3q}{\sigma_M^2}-\frac{3q_2q_1f^*}{\sigma_M}\sinh\left(\frac{-3q_2p}{2\sigma_M}\right)}{\frac{6q}{\sigma_M^2}+\frac{3q_2q_1f^*}{\sigma_M}\sinh\left(\frac{-3q_2p}{2\sigma_M}\right)} \tag{13}$$

With the Taylor series expansion of $\sinh \approx x$ the plastic Poisson's ratio is expressed as

$$\nu_p \approx \frac{3q+\frac{9}{2}q_2^2q_1f^*p}{6q-\frac{9}{2}q_2^2q_1f^*p} = \frac{1+\frac{3}{2}q_2^2q_1f^*\eta}{2-\frac{3}{2}q_2^2q_1f^*\eta} = \frac{1-\frac{1}{2}q_2^2q_1f^*}{2+\frac{1}{2}q_2^2q_1f^*} \tag{14}$$

by using the triaxiality value for uniaxial tension $\eta = -\frac{p}{q} = -\frac{1}{3}$. For this case the deviatoric plastic strain increment can be expressed in terms of plastic Poisson's ratio. By comparison of Gurson's and Barlat's model a correction factor can be identified as follows:

$$\left.\begin{aligned}\Delta\varepsilon_{q,Gurson} &= \left|\Delta\varepsilon_{q,xx}\right|\frac{2}{3}(1+\nu_p)\\ \Delta\varepsilon_{q,Barlat} &= \left|\Delta\varepsilon_{q,xx}\right|\frac{2}{3}(1.5)\end{aligned}\right\}\Delta\varepsilon_q = \Delta\varepsilon_{q,Barlat}\frac{1+\nu_p}{1.5} \tag{15}$$

This leads to the damage evolution for uniaxial tension:

$$\Delta f = \frac{4}{4+q_2^2q_1f^*}\left[(1-f)\Delta\varepsilon_q\frac{3q_2q_1\sigma_M f^*}{2q}\sinh\left(\frac{-3q_2\eta p}{2\sigma_M}\right)+A\Delta\varepsilon_q\right] \tag{16}$$

## 6 Verification on small simulation models

### 6.1 Realisation of the damage evolution during the forming process

The aim of this project is to leave the Barlat material model unaltered and to get additional information for the damage by running the Gurson model in the background. Therefore the damage evolution needs to be adjusted for pressure-independent material models like the Barlat model. This has been described in the previous section and will now be used in the way shown in Figure 4.

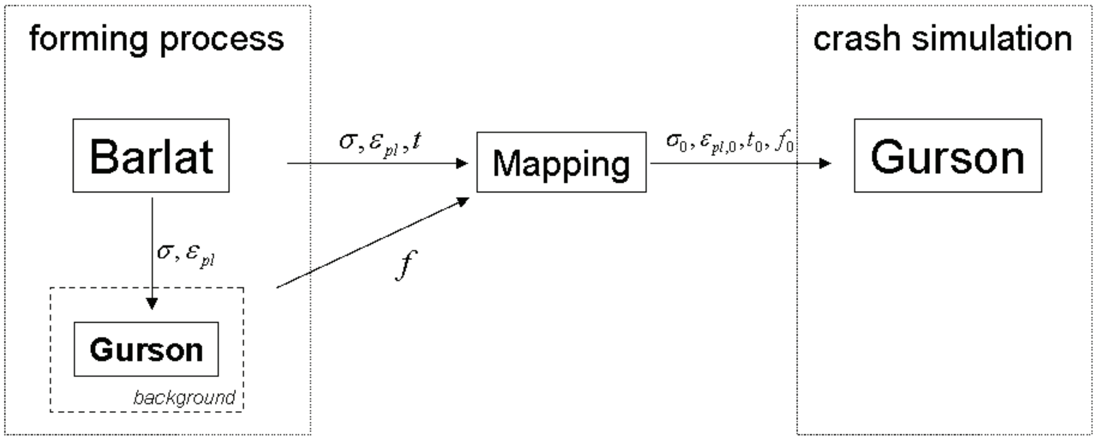
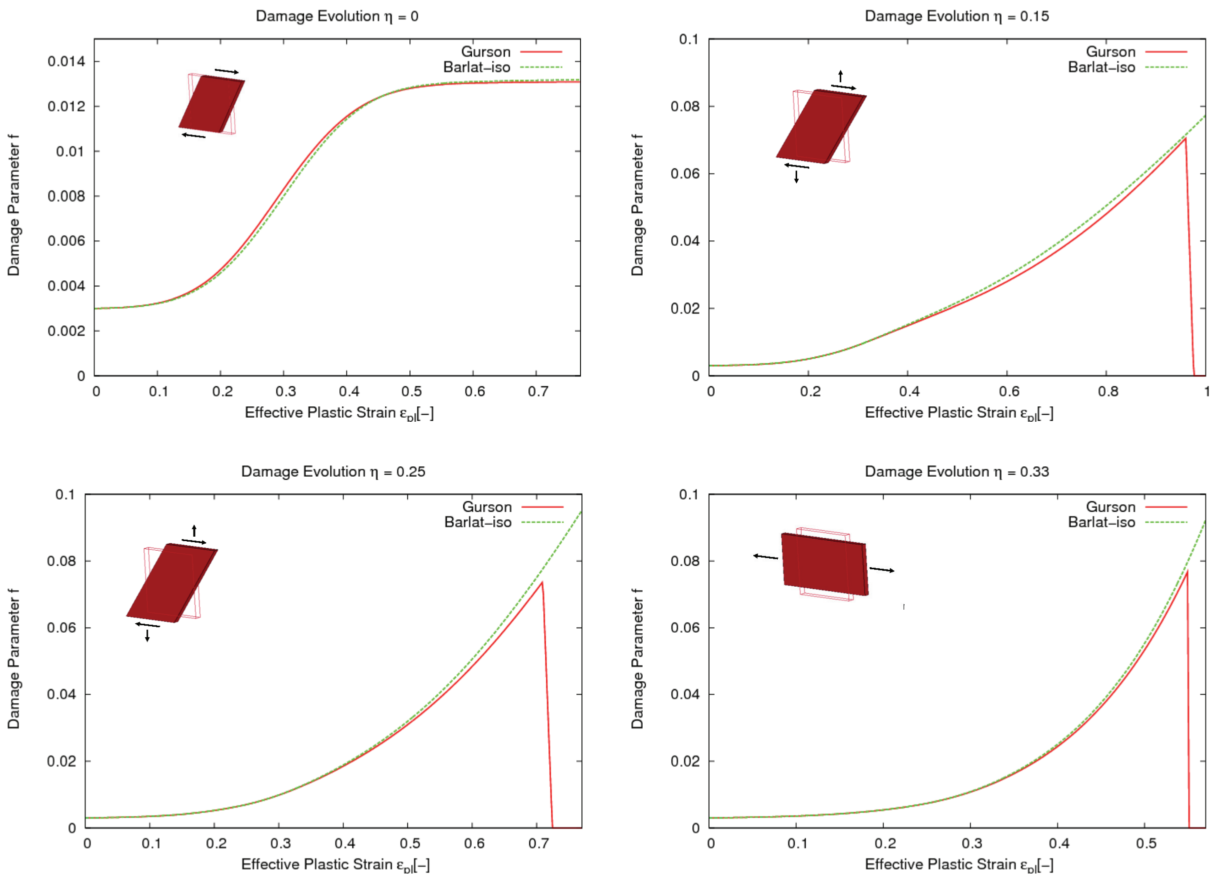



*Figure 4: Relation between the different processes*

### 6.2 Verification on small simulations

The previously derived damage evolution (16) should be able to represent the damage evolution in the original Gurson model. The derived evolution for the uniaxial tension case can be extended by using a scale factor to represent all triaxiality values in the interesting range from $\eta = 0$ to $\eta = \frac{2}{3}$. In order to verify the implemented damage development various small simulation models with varying triaxiality states have been examined under the assumption that the relation between the in-plane plastic strains is constant during loading.



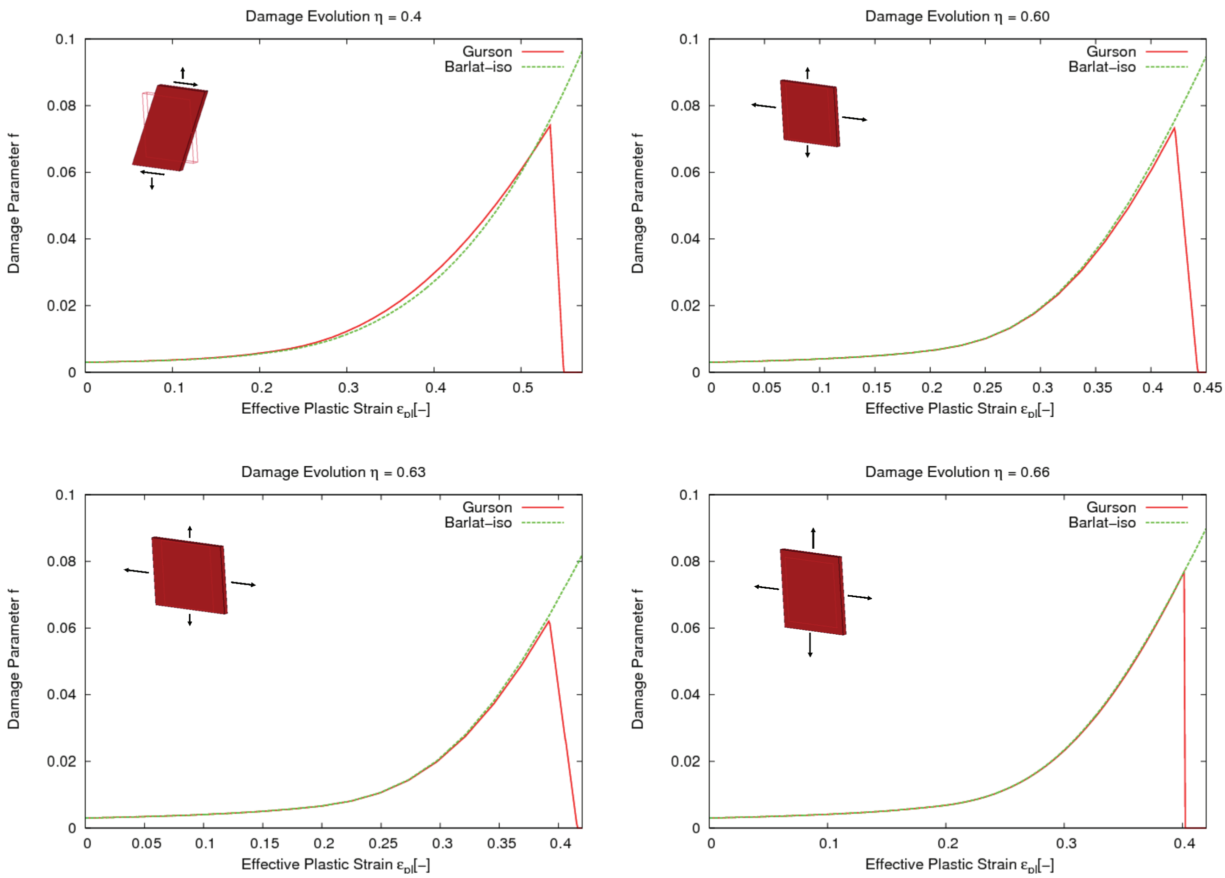



*Figure 5: Damage evolution for various triaxiality states*

It can be noted that the implemented damage evolution leads to a satisfying correlation with the original damage evolution in the Gurson model for the examined triaxiality states.

## 7 Validation on structural components

The successful testing of the implementation in section 6 gives rise to the next step of validation. The use of the damage evolution on structural components will show whether the distribution of the damage is realistic or not. In this case two structural components will be presented - the well known S-Rail and a crossdie geometry.

### 7.1 S-Rail

The S-Rail was initially developed for metal forming process analysis and firstly presented at the NUMISHEET '96. Here it should stand for a small structural component which shows the dimension of the damage evolution.

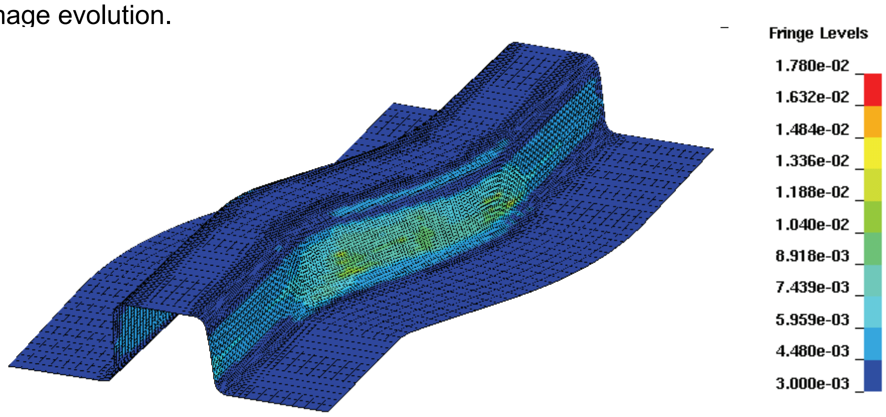



*Figure 6: Damage evolution on the S-Rail*

The forming process was conducted in the usual manner of using the Barlat model with the difference of achieving additional information through the Gurson model running in the background. The damage parameter was written to the history variables table and can be recalled for post-processing The maximum value of the Gurson porosity parameter occurring in the simulation is f = 0.0178. A comparison to the final porosity value leading to failure of $f_f$ = 0.074 for this element length identifies a damage status of max 24%.

### 7.2 Crossdie

The Crossdie is a second structural component which in comparison to the S-Rail undergoes also low and negative triaxiality stress states during the forming process.

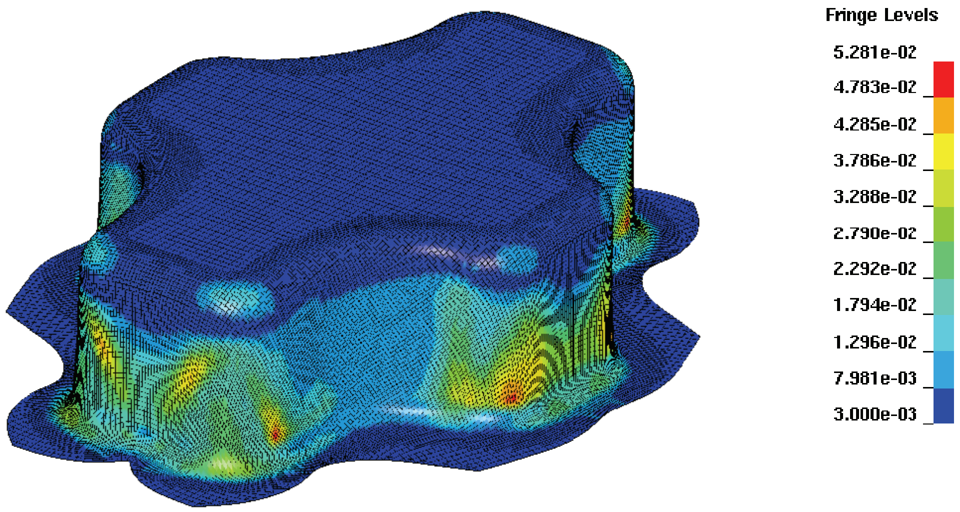



*Figure 7: Damage evolution on the crossdie*

The maximum value of the porosity parameter in this case is f = 0.0528. The comparison to the Gurson porosity parameter at failure of $f_f$ = 0.076 in this case shows a maximum damage state of 69.4%. Experimental results predict for the shown forming state failure in a region which cannot be confirmed by the simulation. Hence both the distribution and the maximum value were not predicted correctly. It must be noted in this context, that the Gurson model is not calibrated for negative or zero triaxiality states. This causes unrealistic damage predictions with respect to the damage distribution. Possible and necessary extensions of the Gurson model are therefore discussed in the conclusions.

## 8 Mapping

The transfer of the damage values in the forming process to the discretization of the crash-simulation is named ‘Mapping’. Two possible ways of the value handover have been accomplished. At the moment the damage parameter f is placed on position 9 of the history variables table in LS-DYNA during the forming process. Yet the Gurson model requires this parameter on position 1 of the history variables table. Therefore the result file (i.e. “dynain”-file) has to be manipulated and the damage parameter repositioned from position 9 to 1 in the history variables table. This procedure has to be done for both ways of mapping that will be discussed next:

- **Using LS-Dyna**: LS-Dyna is able to map the element thickness, the effective plastic strain, stresses and the history variables. It should be noted that it is important that both source and target parts have to be in the same position towards the coordinate system to obtain satisfying results. The advantage of the LS-Dyna internal mapping is that no additional step between the mapping process and the start of the crash simulation is necessary. On the other hand a disadvantage of the LS-Dyna internal mapping process is that extra effort has to be made to reposition the part towards the coordinate system.

- **Using the SCAI-Mapper**: The SCAI-Mapper has the advantage being more user-friendly. The most noticeable positive aspect is the automatic transformation of both parts on top of each other. A minor disadvantage is that it is necessary to include the results as initial values in the input file before running the crash simulation.

## 9 Conclusions

The present contribution highlights the successful implementation of the Gurson damage evolution in a manner that can be used by pressure-independent material models like the Barlat model. The verification on small simulation models results in a correlation of the evolution of the damage parameter in the two different material models. The validation on structural componets showed realistic maximum values and a realistic distribution of the damage parameter on the S-Rail. However, the distribution of the damage parameter on the crossdie displays a non-realistic distribution. The reason, as mentioned above, is that the Gurson damage evolution is not able to predict failure at zero mean stress or negative triaxiality states.

To account the shear dominated failure the Gurson model has to be further extended. This has been realized by a combination of Gurson's damage model with Johnson-Cook's failure criterion [5]. Another promising way is a modification suggested by Nahshon and Hutchinson [4]. They include a contribution to the damage growth rate of the Gurson model for states of pure shear stress. This modification rests hereby on the notion that the volume of voids undergoing shear may not increase, but the deformation and reorientation of voids constitute an effective increase in damage. This extension is based on a second stress measure besides triaxiality, the lode angle parameter. Future research will identify if this is a reasonable way of extending the Gurson model.

## 10 References

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