Recent development and applications of the Gurson model

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Abstract:

With increasing requirements on the crash safety of automotive components and on virtual prototyping it becomes more and more important to model damage behaviour of structural components in crash simulations. Especially high strength steels show a lower ductility in comparison with conventional steels. To predict the damage behaviour an evaluation chain including material charaterization, numerical simulation with a suitable damage model and verification by component tests was established. To vary the stress triaxiality notched flat tensile specimens and Iosipescu shear specimens were tested. The damage behaviour depends strongly on the loading type (stress triaxiality) and cannot be modelled with simple damage models based on one constant fracture strain. In this work, the Gurson model and the Wilkins model have been applied to describe the damage behaviour and failure in crash simulations. The Gurson model has been extended by Johnson-Cook's law in order to improve the ability to represent shear dominated failure.
Special experimental techniques for material characterisation and component tests were developed. The applied damage concept was verified in terms of examples, i.e. a motor carrier of an aluminium die cast alloy and a B-column of a high strength steel.

Keywords:

Material Characterization, Damage Models, Crash Simulation

1 Introduction

The application of new light weight materials e.g. magnesium, aluminium alloys and high strength steels makes damage modelling more difficult since the damage behaviour of these materials is not well-known and many of them show a higher strength but lower ductility in comparison with conventional materials. Although different damage models (cf. [1],[2],[3],[4]) are available in crash codes, most crash simulations do not take into account the influence of damage on the load carrying capacity. The reason for the lack of damage modelling is that it is not clear which damage model gives a reliable prediction and how the damage parameters should be determined.

In this work a motor carrier of an aluminium cast alloy and a component of a high strength steel were characterised under static and crash loading and simulated with a micromechanical damage model and two phenomenological models. The influences of stress triaxiality and strain rate on the deformation and fracture behaviour were characterised experimentally and modelled in the simulation. Since damage parameters depend on element size, the component calculations were performed with parameters calibrated for different element edge length. To verify the damage models and the method for the determination of material parameters, component tests were performed under crash loading.

2 Damage models

Several continuum models have been developed to simulate ductile damage behaviour of metals. The key point in all of them is a dependence of the damage development on stress triaxiality. One successful concept is the micromechanical Gurson model in which the ductile failure process is described by nucleation, growth and coalescence of microvoids. Gologanu et al [5] have extended the Gurson model to describe the evolution of void shape during loading. As alternative to the micromechanical models different phenomenological damage models are available for the simulation of ductile fracture. A disadvantage for the application of the phenomenological damage models is that they require a lot of experimental tests to calibrate the damage parameters.

2.1 Gurson model

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

$$\Phi = \frac{\sigma_e^2}{\sigma_M^2} + 2q_1 f^* \cosh\left(\frac{tr\boldsymbol{\sigma}}{2\sigma_M}\right) - 1 - \left(q_1 f^*\right)^2 = 0 \tag{1}$$

Here, $\boldsymbol{\sigma}$ denotes the macroscopic stress tensor, σ_e the equivalent von Mises stress, σ_M the actual yield stress of the matrix material and f^* the effective void volume fraction given by

$$f^*(f) = \begin{cases} f & \text{if} \quad f < f_c \\ f_c + \dfrac{1/q_1 - f_c}{f_f - f_c}(f - f_c) & \text{if} \quad f > f_c \end{cases}, \tag{2}$$

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

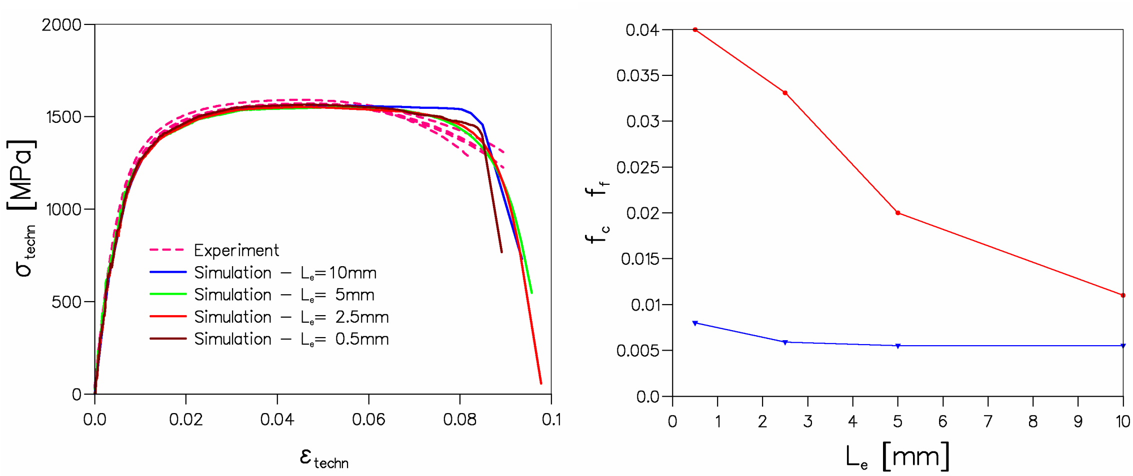
$$\dot{f} = (1-f)tr\dot{\varepsilon}^{pl} + \mathrm{A}\dot{\varepsilon}_M^{pl} \qquad , \qquad \mathrm{A} = \frac{f_n}{s_n\sqrt{2\pi}} e^{-1/2\left(\frac{\varepsilon_M^{pl} - \varepsilon_N}{s_N}\right)^2} \tag{3}$$

The advantage of the Gurson model is the micromechanical motivation and the physical meaning of the damage parameters as porosity. On the other hand, several damage parameters have to be determined.

In most damage models strain softening occurs which leads to a systematic element size dependence of the results. To avoid this, the continuum description must be extended in a nonlocal sense. Several regularization methods have been suggested as e.g. gradient plasticity, Cosserat continua, discontinuus formulations or gradient dependent damage descriptions as shown in [7]. A more practical calibration method has been chosen in [8]. With the Gurson damage parameters depending on the absolute element size l_e

$$f_f = f_f(l_e) \qquad f_c = f_c(l_e) \qquad f_N = f_N(l_e) \tag{4}$$

it is possible to get mesh independent results as shown in Figure 1 and Figure 2. The uniaxal tension specimen is discretized according to the element lengths of interest as shown in Figure 2. For each element size the damage parameters have to be determined. Finally we obtain a functional dependence of the relevant damage parameters over element length which is depicted in Figure 1b. It is interesting to observe the failure mechanism in the simulations with different discretizations. As can be seen in Figure 1a, the global properties like force or displacement are well reproduced by all considered discretizations.



a) b)

Figure 1: a) uniaxial tension results b) Element size dependence of Gurson damage parameters

On the other hand the crack opening mode angle of the experiment is captured only by the finest mesh (l_e=0.2mm) in Figure 2. This order of magnitude is not surprising if we keep in mind that each regularization method to some extend introduces a material inherent length scale or an additional material parameter which can be interpeted physically as a typical microstructural quantity. In metals this length can be identified e.g. by the distance between microvoids.

As mentionned above, the Gurson model has further to be extended to account for shear dominated failure. This has been realized by a combination of Gurson's damage model with Johnson-Cook's failure criterion which will be discussed in the next section.

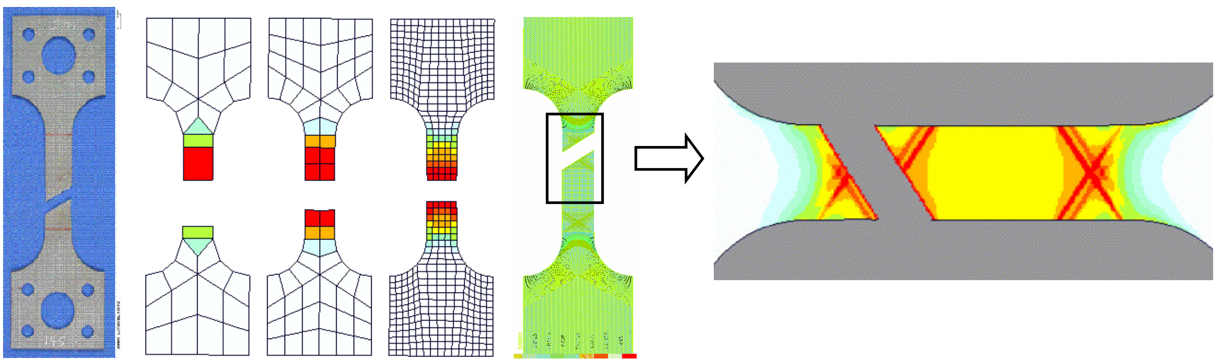


Figure 2: Regularization of damage parameters for uniaxial test specimen

2.2 Johnson-Cook model

The failure criterion of Johnson-Cook [4] is based on a plastic fracture strain which depends on triaxiality (σ_m/σ_e), strain rate and temperature. Failure occurs when the damage variable D reaches the value 1. Equation 4 shows the definition of the damage variable D and the plastic fracture strain ε_f. ε_e^p denotes the von Mises plastic equivalent strain. $\dot{\varepsilon}_e^p$ and $\dot{\varepsilon}_0$ are the rate of the von Mises plastic equivalent strain and of the reference strain. Since temperature was not changed in this work, the term describing the influence of temperature on damage is omitted in equation (5). The material parameters d_1, d_2, d_3 and d_4 have to be determined by specimen tests under different triaxialities.

$$\mathbf{D} = \int \frac{d\varepsilon_e^p}{\varepsilon_f} < 1 \quad , \qquad \boldsymbol{\varepsilon}_\mathbf{f} = \left(\mathbf{d_1} + \mathbf{d_2}\mathbf{exp}(-\mathbf{d_3}\frac{\sigma_\mathbf{m}}{\sigma_\mathbf{e}})\right)\left[\mathbf{1} + \mathbf{d_4}\ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_0}\right)\right]\Lambda \tag{5}$$

In contrast to continuum damage models the Johnson-Cook model uses the von Mises yield condition and the damage variable D does not affect the yield surface. This is a weakness of Johnson-Cook's model because we know that the damage process depends strongly on the hydrostatic part of the stress state. Therefore, a combination of Gurson's pressure dependent damage model with Johnson-Cooks's triaxiality dependent failure criterion [12] has been implemented as MAT_GURSON_JC in LSDYNA (Version 971).

2.3 Wilkins model (D_cR_c)

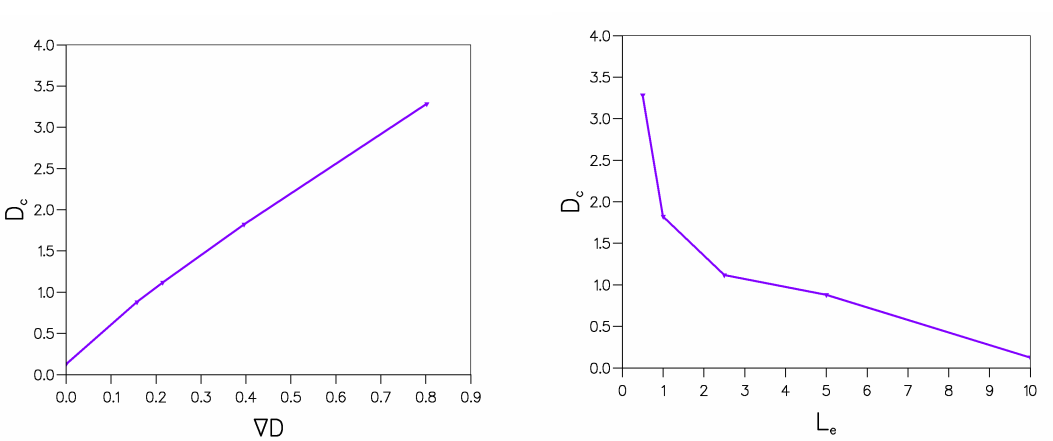
The phenomenological damage model of Wilkins [3], also known as D_cR_c model is considered in this work. According to this model damage occurs when the damage variable exceeds the critical damage value D_c over a critical distance. The damage criterion implemented in the crash code LS-DYNA is given by:

$$\mathrm{D} = \int \omega_1\, \omega_2\, d\varepsilon_e^p \geq \mathrm{D_c} \quad , \qquad D_c = D_0\left(1 + b\left|\nabla D\right|^\lambda\right) \tag{6}$$

$$\omega_1 = \left(\frac{1}{1 - \gamma\sigma_m}\right)^\alpha, \qquad \omega_2 = (2 - A_D)^\beta, \quad A_D = Min\left(\left|\frac{s_2}{s_3}\right|, \left|\frac{s_2}{s_1}\right|\right) \tag{7}$$

w_1 and w_2 are hydrostatic and deviatoric weighting terms. s_1, s_2 and s_3 are the principal deviatoric stresses and ∇D denotes a damage gradient. The Wilkins model has six parameters, α, ß, γ, D_0, λ and b which can be determined by fitting tension, compression and shear tests.

In the Wilkins model a gradient dependence of the critical damage D_c has been added as regularization method (Figure 3). This is leading to a very similar concept like the Gurson model as can be seen if we compare Figure 3 with Figure 1, where the critical damage is depicted over the element size.



a) b)

Figure 3: a) Gradient dependence of Wilkins model b) Element size dependence of Wilkins model

3 Determination of material properties and model parameters

The Gurson model was used to simulate all tests concerning this component. The Gurson model has totally seven parameters which are not independent from each other. Three of them (ε_n, S_n, q_1) were taken from literature [1],[6] and the other parameters (f_0, f_n, f_c and f_f) were determined by simulating the tension tests on the smooth specimens. At the beginning of the simulation the initial porosity f_0 and the volume fraction of void forming particles f_n were selected on the basis of results of similar materials and the corresponding critical parameters f_c (porosity at coalescence) and f_f (porosity at fracture) were determined by fitting the calculated displacement at fracture to the measured values.
Figure 4 shows that the Gurson parameters obtained from the smooth tension specimens can be used to predict the damage behaviour of notched specimens with two different notch radii. The dependence of damage behaviour on loading type which is characterised by the stress triaxiality σ_m/σ_e is quantified by tension tests on smooth and notched specimens and shear tests. As expected, the measured fracture strain decreases with increasing triaxiality. The three damage models i.e. Gurson, Johnson-Cook and Wilkins were applied to simulate the tension and shear tests. While only a tension test is required for the determination of the Gurson parameters, three types of experiments under tension, shear and compression are needed for the identification of parameters for the Johnson-Cook and Wilkins models. All three damage models gave a good prediction of the deformation and fracture behaviour of the smooth and notched tension specimens with the calibrated parameters.
Figure 4 shows further the influence of the triaxiality on the failure strain. Obviously, the Gurson model is able to describe ductile failure for stress states in smooth or notched tension specimen.

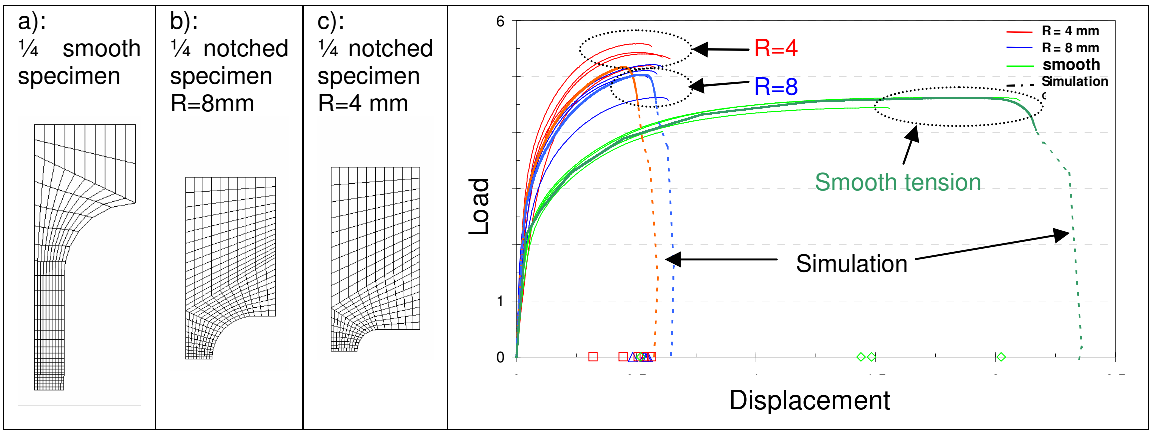


Figure 4: Finite element meshes for smooth and notched flat specimens and comparison between the measured and simulated load vs. displacement curves of the different tension tests

The numerical results obtained for the modified Iosipescu shear tests are interesting for the comparison of the three damage models. The test set up of the modified Iosipescu shear test shown in Figure 5 corresponds to an asymmetric four point bending and the cross section between the two notches is loaded under pure shear [9]. The measured nominal stress vs. displacement curves are shown in Figure 6 in comparison with the results calculated with the Gurson model and the Johnson-Cook model. The Johnson-Cook model can predict the shear failure using the parameters calibrated before. The Wilkins model shows the similar result as the Johnson-Cook model. The Gurson model overestimates the displacements at failure of the Iosipescu specimens. This is not surprising because the void growth in the Gurson model depends only on the hydrostatic stress. Thus, shear deformation does not influence the damage process in the Gurson model which is not correct in general.

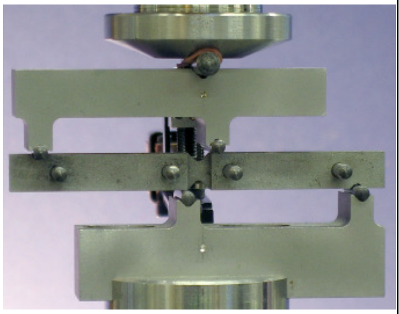


Figure 5: test set up of the modified Iosipescu shear test

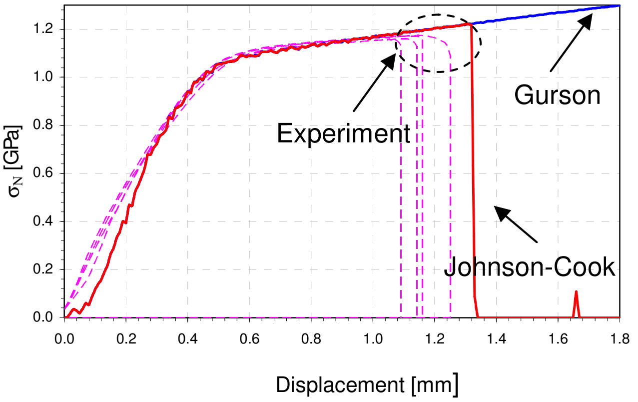


Figure 6: measured and calculated nominal stress vs. displacement curves of the Iosipescu shear tests

A detailed analysis of the fracture process of a Iosipescu specimen gives the indication that the first damage occurs not in pure shear region between the both notches but in a tension region close to the notch root. After the damage initiation the rupture of the Iosipescu specimen occurs though shearing. Figure 7 shows the damage pattern of the Iosipescu specimen from experiment and simulations.

Experiment	Gurson	Johnson-Cook

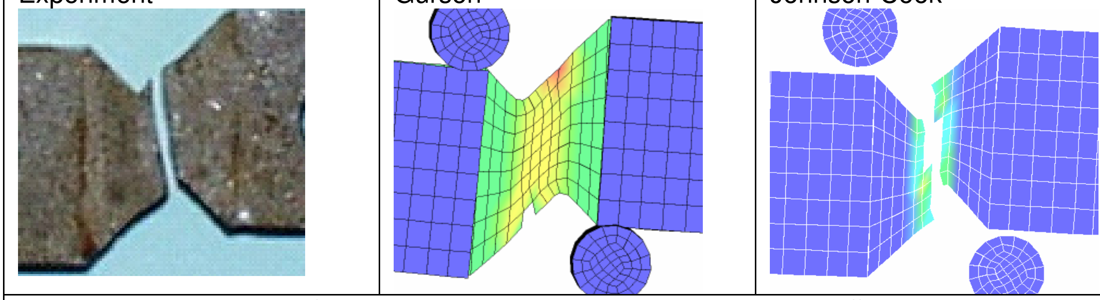


Figure 7: damage pattern of a Iosipescu specimen in experiment and in two different simulations

The Gurson model can predict the damage initiation under tension but cannot predict the following propagation of the micro-crack through shearing. To overcome the weakness of the Gurson model the Johnson-Cook fracture criterion was implemented into the Gurson-model as an additional criterion for the triaxiality between pure shear and uniaxial tension.

In Figure 8 the whole test program for determining the damage parameters is summarized. For the Iosipescu shear test we have a triaxiality not exactly but close to zero because the ductile material behaviour locally is leading to an overlay of tension stresses. By notching of tension test specimen we can reach higher triaxiality values so that the use of smooth uniaxial tension tests is completed by inserting two different notch radii.

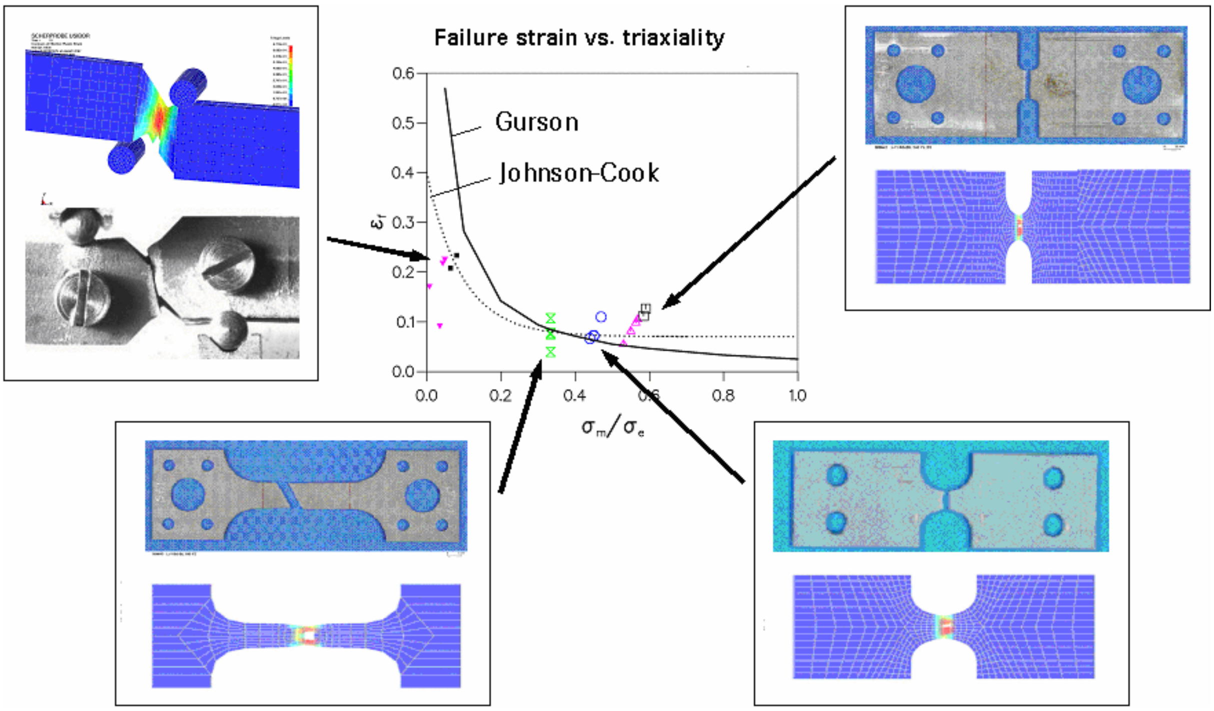


Figure 8:Test program for determination of triaxiality influence on failure strain

Whereas the triaxiality curve of the Johnson-Cook model must be defined explicitly by the parameters d_1 and d_2 , the corresponding curve of Gurson's model is a result of the complex dependence on the hydrostatic stress. As expected we can see the weakness of Gurson's model for vanishing triaxiality, where the failure strain is approaching asymptotical to infinity.

4 Crash analysis of aluminium die cast components

4.1 Motor carrier

The crash behaviour of a motor carrier of an aluminium die cast alloy as shown in Figure 9 was characterised and simulated on three scale levels i.e. tension specimens, sections cut from the component as marked in Figure 9b and the whole component.

a) b) c) d)

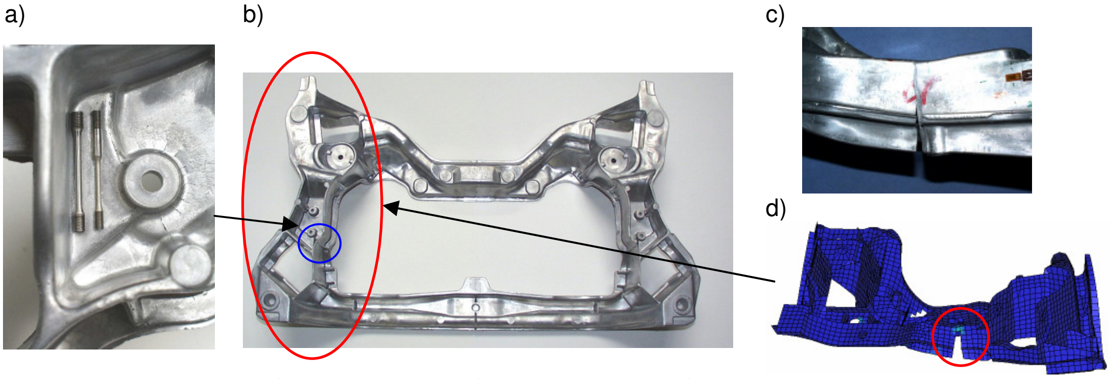


Figure 9: a) one position for the extraction of tensile specimens from the automobile component, b) geometry of the automobile component of an aluminium cast alloy, c) a section of the automobile component after bending test, d) prediction of damage behaviour of the component section by crash simulation

Round and flat tension specimens were taken out from different positions in the component and tested under static and dynamic loading. To study the influence of stress triaxiality on the damage behaviour, smooth and notched specimens were used. It was found that the flow stress $R_{p0.2}$ and the ultimate tensile strength R_m depend slightly on the position for the specimen extraction. The fracture strain A and the reduction of area Z show a more pronounced dependence on the position in the component. The dynamic stress vs. strain curve at strain rate of 100/s lies remarkably over the static curve (about 20% higher at R_m).
To verify the applicability of the Gurson model and its damage parameters for component simulations, a component section was cut out from the motor carrier and tested under static and dynamic bending. In comparison to the crash test on the whole component the boundary conditions for the bending test on the section are simpler and can be easier modelled in the simulation. The finite element model for the section (Figure 9d) was built with shell elements with an element edge length of about 5 mm as used in vehicle simulation. Since the Gurson parameters are not independent of element size [7], they were calibrated by modelling a tension test on a smooth flat tension with different element sizes. It was found that in this case it is sufficient, only to calibrate the f_f-value as a function of element edge length. In a special version of the crash code LS-DYNA this relationship between the Gurson parameter f_f and element edge length can be used for component simulations. Using the Gurson parameters calibrated for different element sizes the damage behaviour of the component section under bending (Figure 9c) was very well simulated (Figure 9d).
Crash tests on the whole component were performed at DaimlerChrysler. During the crash test three corners of the component were fixed and the other corner was pressed by an impactor. One of the crash tests was simulated with the damage parameters determined from tension tests and used for the simulation of the bending test on the component section. The deformation pattern and the load vs. displacement curves from experiment and simulations are compared in Figure 10 and Figure 11. The characteristic of the measured load vs. displacement curve was well predicted by the simulation with the Gurson model. The simulation without taking damage into account overestimates the maximum load and especially the absorbed energy dramatically.

Figure 10: an automobile component of an aluminium die cast alloy after crash test and result of crash simulation

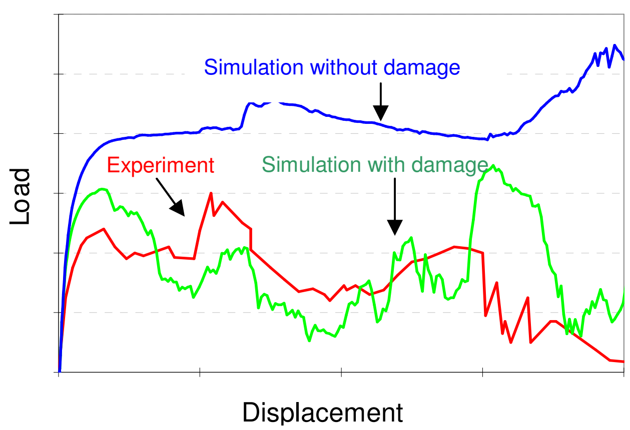


Figure 11: measured and predicted load vs. displacement curves of an automobile component under crash loading

4.2 Die cast profile

In a second example a Aluminum die cast profile is considered in a three-point-bending load case. The identification of damage parameters has been conducted following the procedure presented above. Only the Gurson-Johnson-Cook model is applied. A regular mesh with average element size of 5mm has been used. A special focus was set on the extraction of the yield curve from technical stresses and strains, especially after onset of necking in the tension test specimen as shown in [11].
The result is shown in Figure 12. It was found that in the simulation the crack was captured well even with the use of slightly different yield curves. Of course, the force-displacement curve is much more

sensitive to those changes. Only the correct extraction of the yield curve are well reflecting the experimental results.

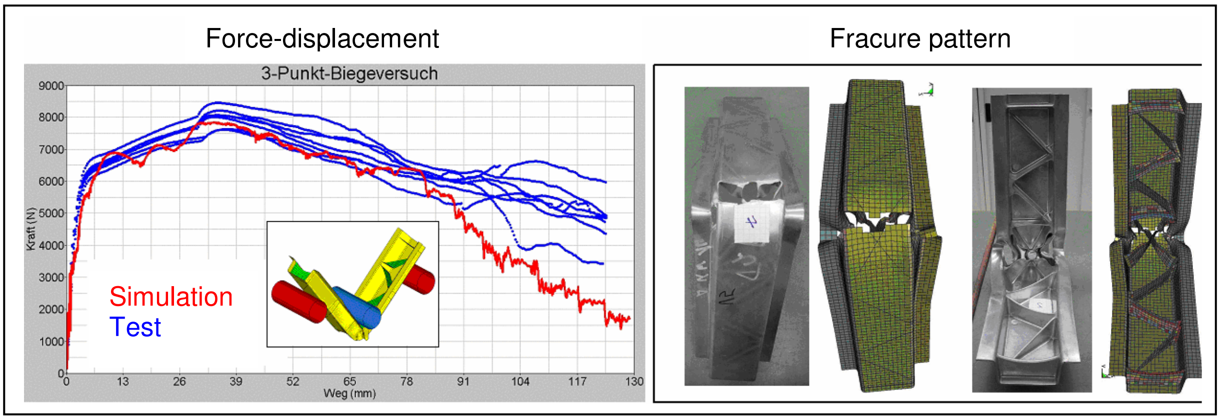


Figure 12: Experiment and simulation of an Aluminum die cast profile

5 Crash analysis of components of high strength steel

A prototype component of a high strength steel was produced by drawing at high temperature and cooling in the forming tools (press hardening). To characterise the local mechanical properties sub-sized flat tension specimens were taken out from different positions in the component (Figure 13) and tested under static and dynamic loading. Figure 13 shows the engineering stress vs. engineering strain curves for the different positions. The specimens from the upper area of the component deliver a much higher yield stress and ultimate strength than the specimens from the side area. It might be caused by variation of local cooling rate during the process of the press hardening. The influence of the inhomogeneity of material properties in the component on the crash behaviour of the whole component was investigated by simulations.

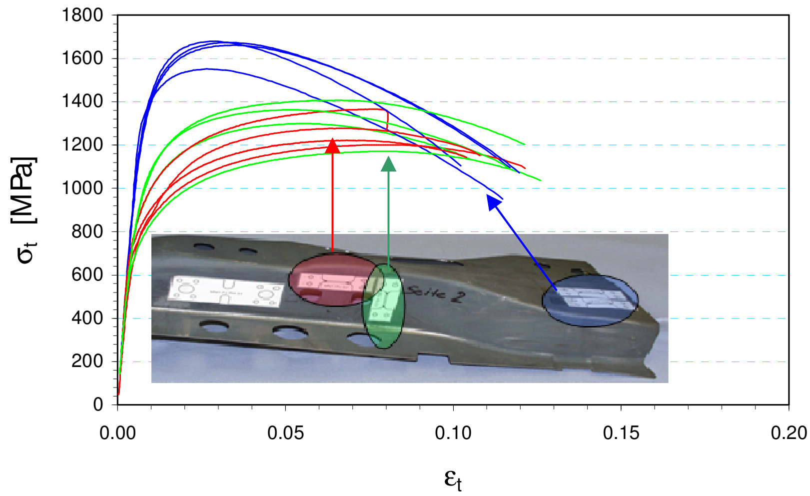


Figure 13: measured nominal stress vs. nominal strain curves from three positions in a automotive component of a high strength steel

The component was tested under static and dynamic three-point bending. The damage models (Gurson, Johnson-Cook and Wilkins) were used to simulate the component tests. The element edge length in the models of the component is about 5 mm. The damage parameters for the three damage models were calibrated for different element sizes by modelling a tension specimen. Figure 14 shows the measured and calculated deformation behaviour and the load vs. displacement curves of the component tests. It can be recognised that the results obtained with the Gurson model and the Johnson-Cook model are in better agreement to the experiments as the Wilkins model. This may surprise because of the demonstrated weakness of the Gurson model in shear dominated damage processes. The reason is that the boundary conditions of this test configuration did not enforce shear dominated failure.

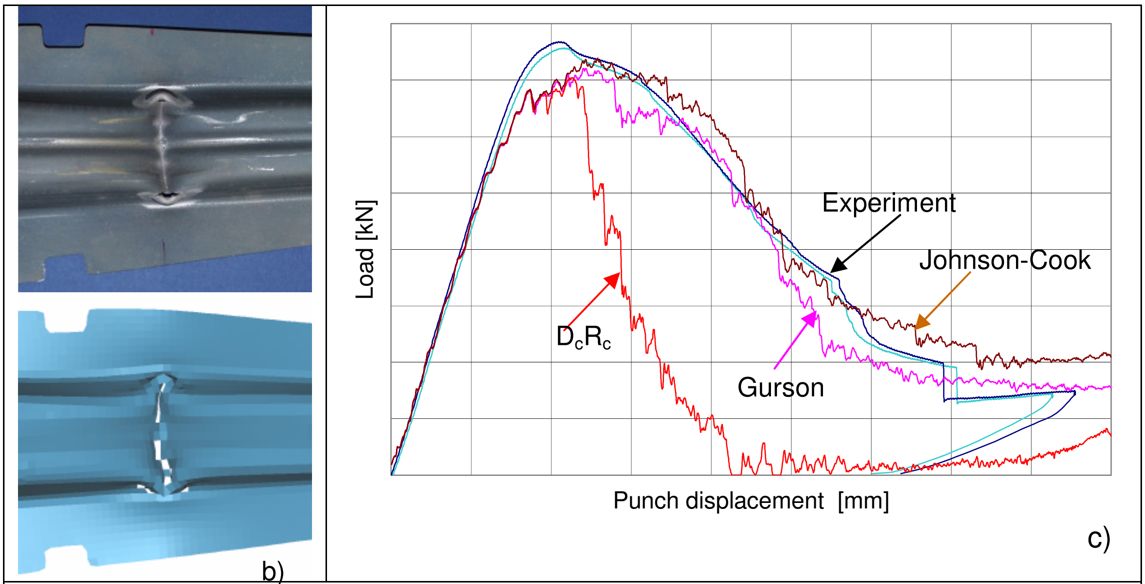


Figure 14: a) damage pattern in experiment, b) calculated damage with the Gurson model, c) measured and calculated load vs. displacement curves of a component of a high strength steel

5.1 Component assembly of high strength steel

A more complex component assembly under dynamic three-point-bending conditions is investigated. For all involved material grades the Gurson-Johnson-Cook damage parameters have been identified following the procedure outlined above. The simulation result is in good agreement to the experiment if we compare the global deformations and crack paths in the component assembly in

Figure 15. Of course, the agreement is limited if we start focussing in any detail. but this is not surprising if we keep in mind that the reproducability of the experiment also has its limits. Furthermore, we have to take into account that the prediction of cracks in general is a very sensitive task in which the whole manufacturing process chain from rolling, heating, forming and joining has a significant influence on the damaging behaviour of parts.

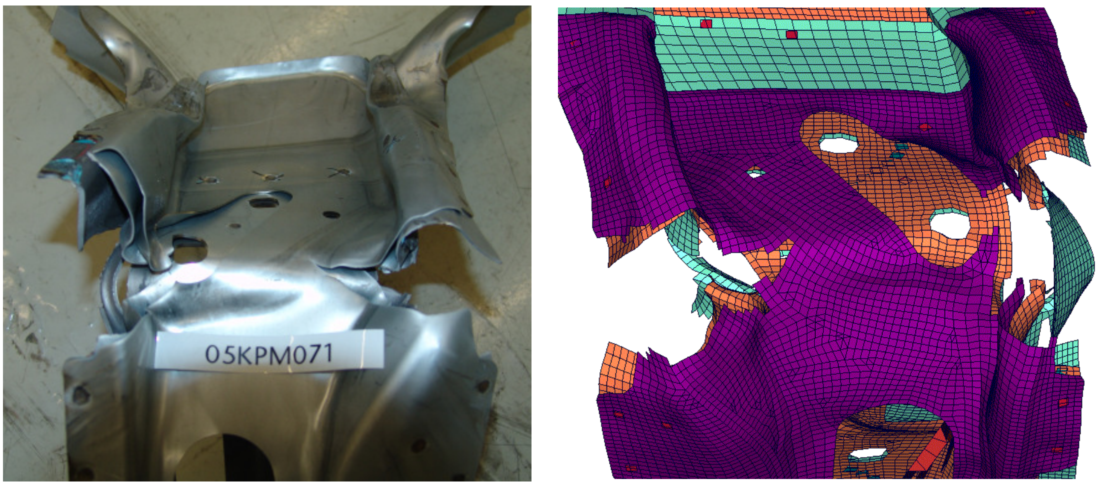


Figure 15: 3-Point-Bending test on a component assembly

6 Conclusions

Relevant characterisation and reliable modelling of material deformation and damage behaviour are necessary for the assessment of crash safety of load-bearing components especially of new light weight alloys. To prove crashworthiness an evaluation chain including material characterization, numerical simulation with a suitable damage model and verification by component tests has been established. Phenomenological damage models like Wilkins and Johnson-Cook and micromechanical models like Gurson describe the influence of stress triaxiality on damage development and were used for component simulations. The phenomenological models require more experiments than the micromechanical models. The weakness of the Gurson model for shear failure was overcome by using an additional damage criterion for the region between pure shear and uniaxial tension.

Besides triaxiality (loading type) and strain rate inhomogeneity of local properties which is caused by micro-structural defects like porosity in cast parts and by different local deformation grades and cooling rates has a large influence on the damage behaviour of a component. Additionally, the element-size dependence of the damage parameters has to be calibrated for component simulations. The applicability of the damage models for crash simulations was demonstrated with automotive components of Aluminum die cast alloy and high strengt steel.

7 References

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