On Calibrating Advanced Damage Models Using Sheet Metal Coupon Tests

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Abstract:

With increasing requirements on crashworthiness and weight reduction of car body structures, the use of high strength steels has become widespread in modern cars. In contrast to conventional steels, these higher strength steels often show significantly less ductility. In crash loadings this fact can cause crack formation, which must be predicted in crashworthiness simulations. In crashworthiness simulations, several continuum models are available which consider ductile damage. One widely used model is the Gurson model. In the near past, several modifications of the Gurson model were presented, to cure a well-known weakness of this model: No damage evolution is predicted in states of zero mean stress. Due to these extensions, the micromechanical Gurson model is able to describe damage accumulation in states of shear stress. Another damage model, which is able to describe ductile damage, is the GISSMO model. This work is considering possibilities for calibrating advanced damage models and the requirements to ensure calibration.

Keywords:

Damage Models, Crash simulation

1 Introduction

Although crashworthiness simulations have been successfully used for the development of automotive structures, their accuracy still has to be improved. Because of increasing requirements on crashworthiness and light-weight structures, advanced high strength steels are more often used in modern car body structures. More accurate modelling of damage evolution of high strength steels is one necessary improvement for crashworthiness simulations.
Because these materials often show less ductility than conventional deep-draw steels, a precise prediction of failure is getting more and more important in crash simulations. Even pre-damage from forming must be taken into account. Therefore, material models have been developed to consider damage evolution during forming operations and to transfer it into crash simulations.
The purpose of this work is to introduce two of these new damage evolution formulations. In addition to this, methods for calibrating complex damage models are investigated.

2 Advanced Damage Models

Investigations of Wierzbicki *et al.* [6], as well as Barsoum and Faleskog [1] exposed that damage evolution seems to depend on more than one parameter. They realized that a definition of damage depending on triaxiality alone is not adequate. The third invariant of stress, which is a measure of the Lode angle, should also be taken into account.
One opportunity to regard this behaviour is a failure criteria presented by Neukamm *et al.* [4], GISSMO can be linked with any material model.
Nahshon and Hutchinson [3] proposed an extension for the micromechanical Gurson model, which accumulates damage in states of shear stress in dependence of the Lode parameter. These two models will be discussed in this paper.

2.1 A new failure criterion: GISSMO

The „Generalized Incremental Stress State dependant damage MOdel“, was first presented in Neukamm *et al.* [4]. It is a new developed failure criterion, based on the well known damage model of Johnson and Cook [2], which can be linked with any material model.
There are two significant differences between GISSMO and the Johnson-Cook model. In contrast to the linear formulation by Johnson and Cook, damage development of GISSMO can be defined as an exponential function, which was also proposed by Xue [8]. In that work, the formulation is motivated by consideration on low cycle fatigue.

$$\dot{D}_f = \frac{n}{\varepsilon_f} D_f^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}_p \tag{1}$$

Using an exponent $n = 1$ leads to the linear Johnson-Cook formulation. With an increasing value of this exponent, a more realistic behaviour similar to a micromechanical damage model, like the Gurson model, can be reached.
The required input data is the second important difference. GISSMO uses a loadcurve of equivalent plastic strain at failure versus triaxiality. This curve can be defined easily, if suitable test data is available. Fig. 1 shows an example of such a loadcurve, containing results of four different coupon tests.

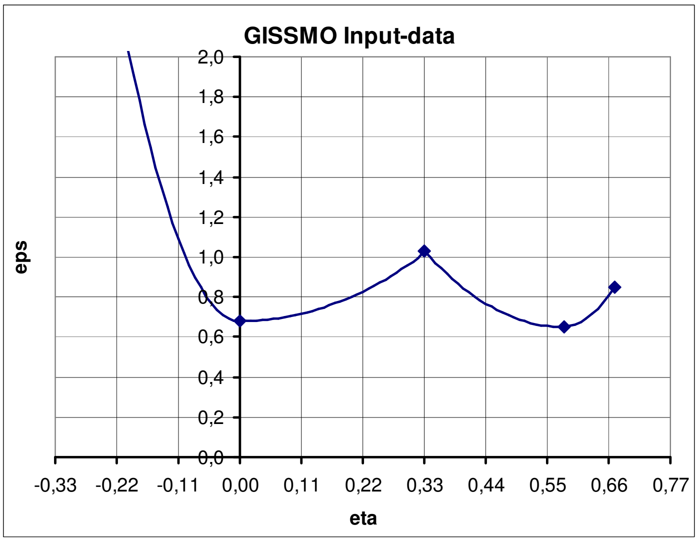

Fig. 1 GISSMO Input-data, failure strain versus triaxiality for plane stress

2.2 Extension of the Gurson Model to predict failure under shear loadings

The micromechanical Gurson model is widely used in crash simulations, to describe ductile failure development. In this physically motivated model, damage evolution is linked to the growth of voids. In shear dominated load cases, the growth of voids vanishes, additionally only few voids are nucleated. So the Gurson model is not able to predict damage evolution under shear loading.

Nahshon and Hutchinson [3] proposed an extension of the Gurson model, which incorporates damage growth under low triaxiality straining for shear-dominated states. The yield function of the Gurson model is retained in this phenomenologically based modification. Only the equation of damage evolution is changed. The new expression leads to:

$$\dot{f} = \dot{f}_{Gurson} + k_{\omega} f \omega (1 - f) \sigma_M \frac{\Delta \varepsilon_q}{q} \tag{2}$$

The function ω(σ) is an additional stress measure to distinguish between axisymmetric and plane strain states, making use of the third invariant of stress.

The single new parameter inside this modification is k_{ω}, which sets the magnitude of damage growth rate in pure shear states.

Nahshon und Hutchinson proposed a function ω(σ), which leads to a symmetric failure surface in invariant space. Investigations of Wierzbicki [6] showed that an asymmetric failure surface may also be possible for some materials. Due to these results, a more general formulation has been implemented in LS-DYNA which enables an asymmetric surface as well as a symmetric one.

$$\omega = 1 - \xi^2 - \beta \cdot \xi (1 - \xi) \tag{3}$$

including an additional parameter β, controlling the asymmetry of the failure surface.

3 Calibration of the Gurson model with Hutchinson extension

The Gurson model will be able to predict damage evolution in shear loadings, if the extension of Nahshon and Hutchinson is used. Depending on the Lodeparameter ξ, which is a measure of third invariant of stress tensor, the Gurson failure curve gets extended to a three dimensional failure surface. The unmodified Gurson model is not depending on ξ, so failure strain is constant in ξ-direction, see Fig. 2.

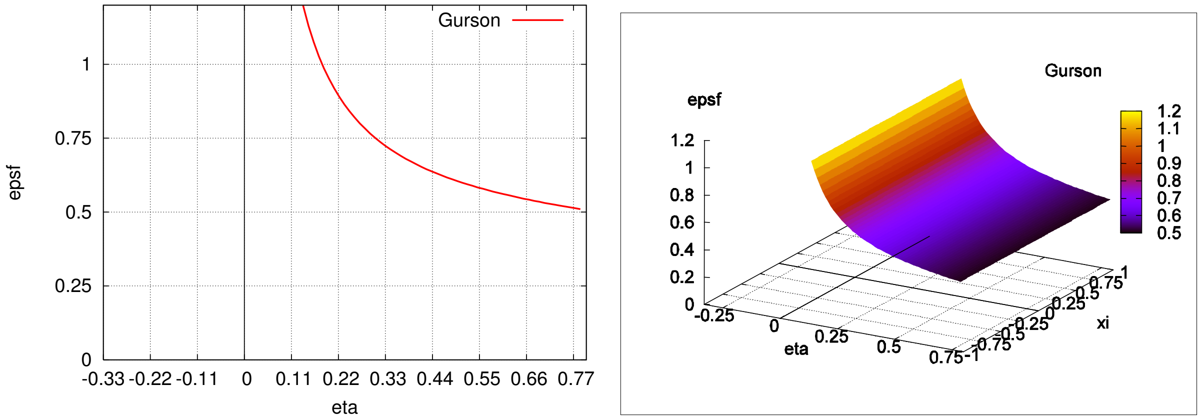

Fig. 2: Gurson model, failure curve and failure surface

The main modification in the extended model is the function ω(σ). A parameter k_ω controls damage growth in pure shear states. The higher k_ω is chosen, the more damage will be accumulated in shear (η=0), compare Fig. 3. In addition to that, plane strain states (η=0.58) are influenced by k_ω, this relation will be explained later. States of uniaxial and equibiaxial stress (η=0.33 and η=0.67) are staying unaltered in contrast.

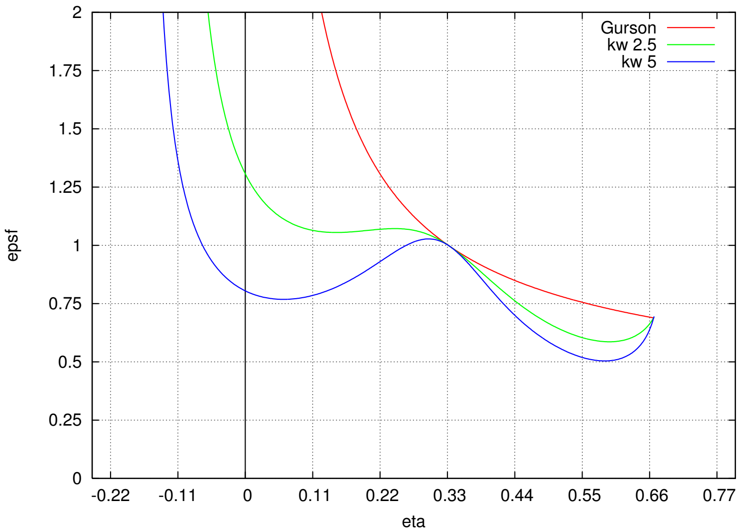

Fig. 3 Gurson-Hutchinson failure curve for different values of parameter k_ω

The parabolic function ω(σ) leads to a spherically warped failure surface. This surface can be defined either symmetric (Nahshon and Hutchinson suggestion) or asymmetric (Wierzbicki suggestion). The parameter β is used to control the asymmetry. Fig. 4 shows three failure surfaces for three different β-values.

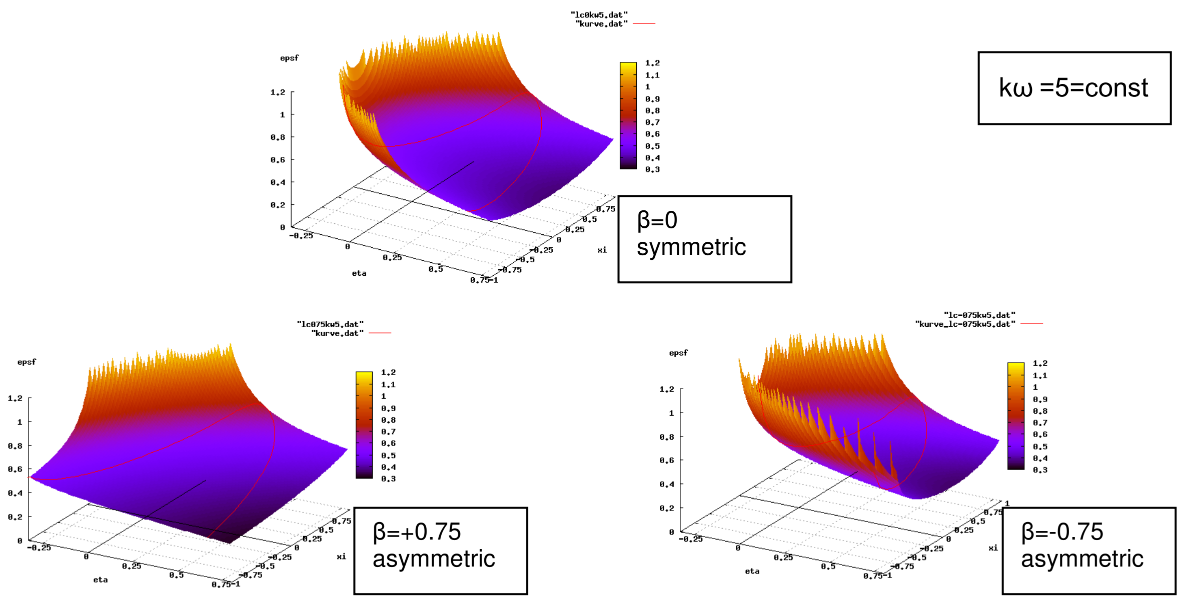

Fig. 4: Gurson – Hutchinson Failure surface, different values of β

For plane stress states, the Lode parameter ξ can be described as a function of triaxiality η:

$$\xi = f(\eta) = -\frac{27}{2}\eta^3 + \frac{9}{2}\eta \tag{4}$$

Due to this, the failure surface can be simplified to a three dimensionally warped failure curve.
A top view onto one of these failure surfaces shows in which way different stress states can be recognized.

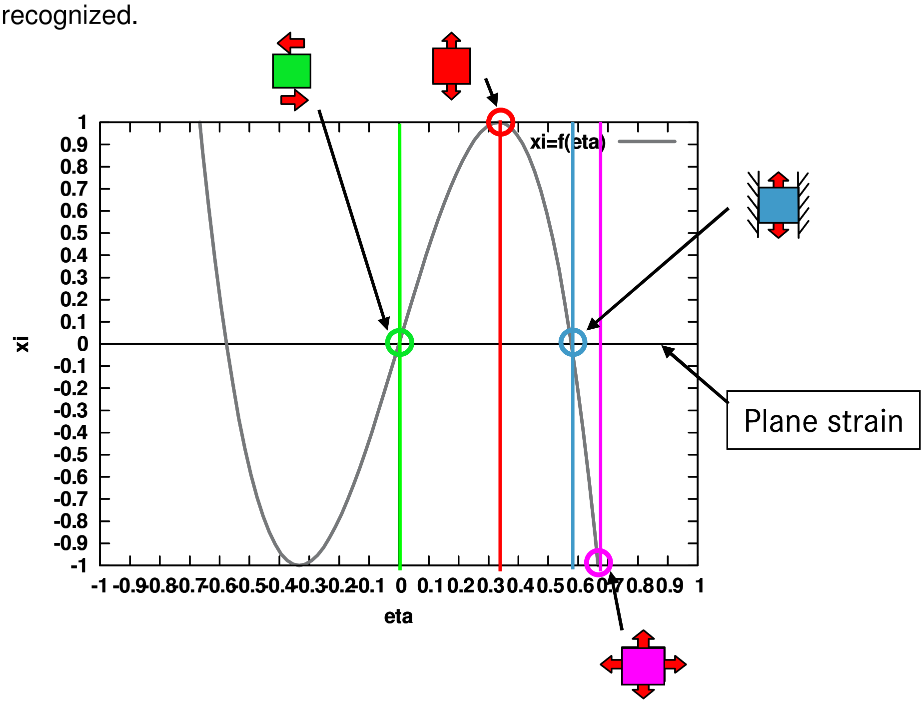

Fig. 5 Lodeparameter ξ for plane stress

For each plane state of stress and its characteristic triaxiality η, a value of ξ exists.
- Pure shear: η=0 → ξ=0
- Plane strain: η=0.58 → ξ=0
- Uniaxial stress: η=0.33 → ξ=+1
- Equibiaxial stress: η=0.67 → ξ=-1

An identical value ξ=0 results for states of pure shear stress and plane strain. Consequently these two states of stress cannot be calibrated independently.
Because ξ is a function of triaxiality η, this curve can be projected onto a plane of a constant ξ-value. Plotting the Gurson-Hutchinson failure curve into a two dimensional chart clearly shows the influence of parameter β on damage evolution, for different triaxialities.
Pure shear (η=0), uniaxial stress (η=0.33) and plane strain states (η=0.58) do not depend on β. But it is recommended to use β to calibrate rupture strain for states of equibiaxial stress (η=0.67).

The procedure to calibrate input parameters for this model should be:
- Calibration of Gurson parameters for states of uniaxial tension
- Adaption of k_ω for states pure shear or plane strain
- Adjusting β for states of equibiaxial tension

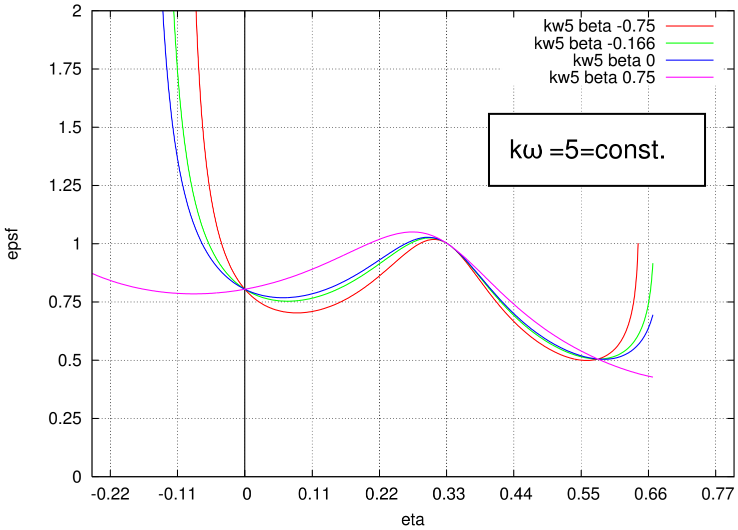

Fig. 6: Gurson-Hutchinson failure curve for different values of parameter β

4 Simulation of Coupon Tests

To ensure the calibration of a complex damage model, such as the Gurson model with Hutchinson extension, testing results of several different component tests are necessary. Results of uniaxial tensile tests alone are not sufficient. More information regarding on different states of stress is required.

A testing program with different coupon tests is simulated in LS-DYNA to find out which triaxialities can be expected. Several different geometries are used to cover the whole bandwidth from states of shear stress to equibiaxial stress. These specimens are presented in the following. Some of the geometries are used by courtesy of Dr. Sun, IWM Freiburg [7]

Shear stress specimens (see Fig. 7)
expected triaxiality bandwidth: 0 < η < 0.33
- Iosipescu
- Arcan
- Scherzug R1 and R0.5

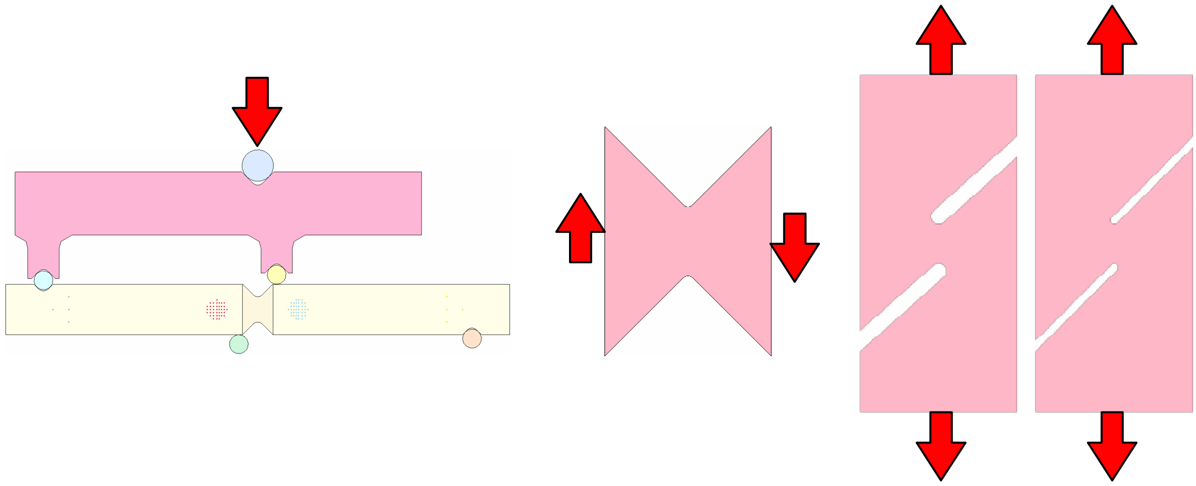

Fig. 7: Shear test specimens: Iosipescu, ARCAN, Scherzug R1 +R0.5

Tensile test specimens (see Fig. 8)
expected triaxiality bandwidth : 0.33 < η < 0.58
- Mini-MPA
- FzR4
- FzR1

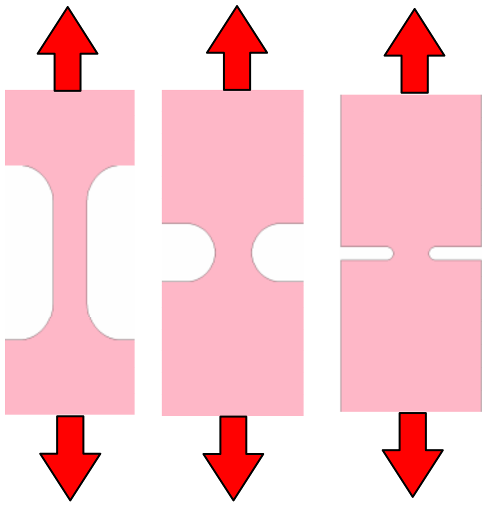

Fig. 8: tensile test specimens: Mini-MPA, FzR4, FzR1

Biaxial tensile test specimens (see Fig. 9)
expected triaxiality bandwidth : 0.58 < η < 0.67
- Nakazima 70mm and 90mm

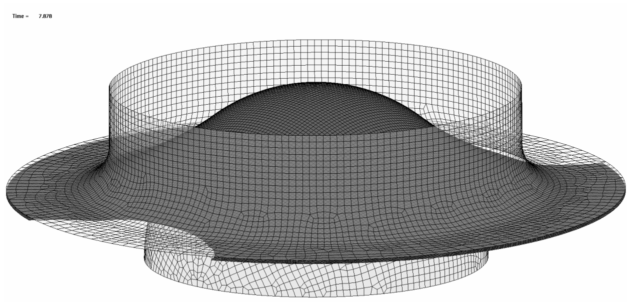

Fig. 9 biaxial tensile test specimens: Nakazima 70mm and 90mm

All failed elements are taken into account to reveal which states of stress exist at the different specimens. Charts of plastic strain versus triaxiality, as well as triaxiality versus time are drawn. As an example, these charts for uniaxial tensile test specimen Mini-MPA (Fig. 10) and Iosipescu shear test (Fig. 11) are shown.
As can be seen, triaxiality of uniaxial Mini-MPA test mainly is as expected, η=0.33. With increasing equivalent plastic strain, triaxiality is changing to a stress state of plane strain $\eta\approx$0.58. The explanation is confinement of lateral strain for these elements. Approximately though, this specimen can be considered as showing uniaxial stress states.

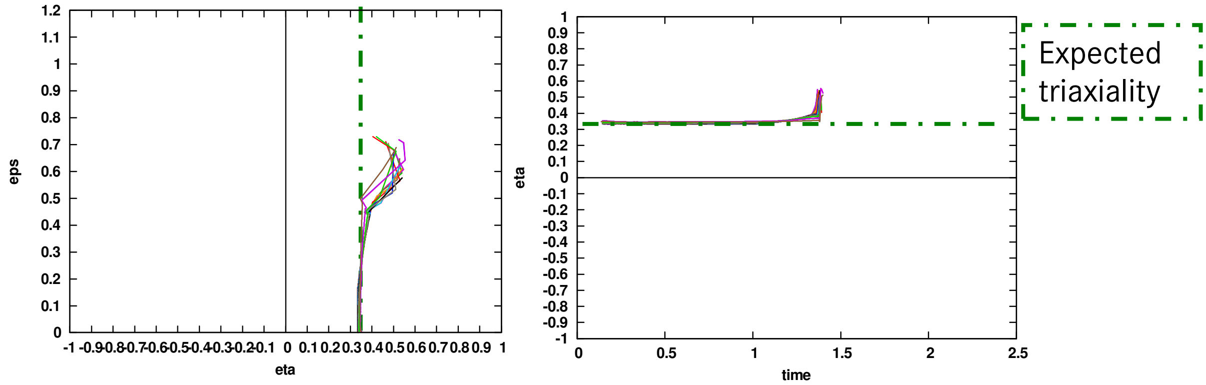

Fig. 10: Result of uniaxial tensile test; plastic strain vs. triaxiality and triaxiality vs. time

The Iosipescu test simulation results are visible in Fig. 11. One disadvantage of the Iosipescu test can be recognized. Because of its kinematics, triaxiality changes from states of pure shear to states between shear and uniaxial stress. Here triaxiality reaches values of $\eta\approx$0.1, which can be considered as a state of shear stress combined with uniaxial tension.

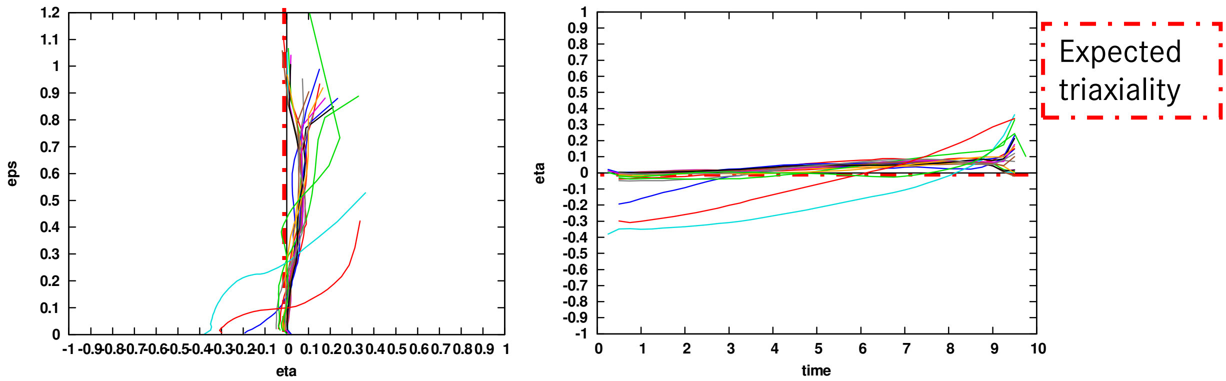

Fig. 11: Result of Iosipescu shear test; plastic strain vs. triaxiality and triaxiality vs. time

This evaluation can be done for all different specimens. Simulations are made using a Gurson-Hutchinson material card as well as a GISSMO material card. Results are presented in the following two diagrams. Average values of failure strain are plotted versus average triaxiality for each specimen. First it should be noted that the Gurson model with Hutchinson-extension is able to predict failure in states of pure shear stress. In addition to that, the used testing program covers the whole bandwidth of triaxiality between states of pure shear and equibiaxial stress. The curve in Fig. 12 was calculated with a FORTRAN program, whereas the GISSMO failure curve in Fig. 13 is the input loadcurve.
Results in states of shear stress differ a lot between GISSMO and Gurson-Hutchison. This can be explained by the fact that states of shear stress and plane strain cannot be calibrated independently, also see section 3. A decision had to be made either to calibrate to shear test results or plane strain

test results. This discovers an advantage of the GISSMO model, test data can be used as input directly. In contrast to that, the Gurson-Hutchinson formulation demands for some calibration effort.

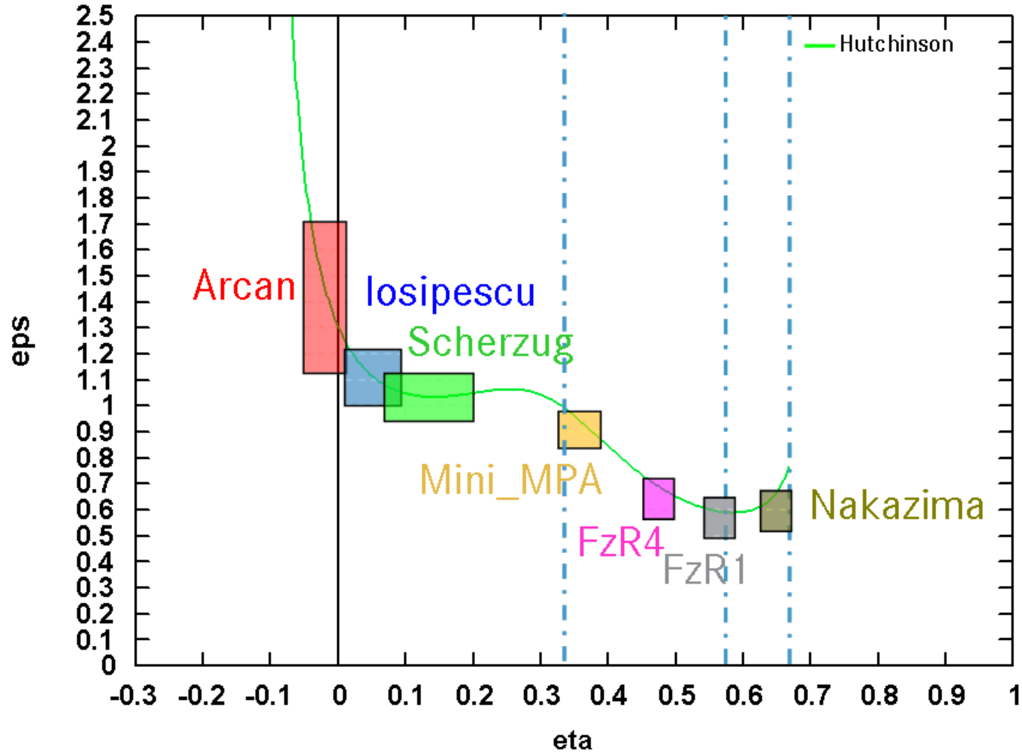

Fig. 12: Simulation results; Gurson with Hutchinson extension

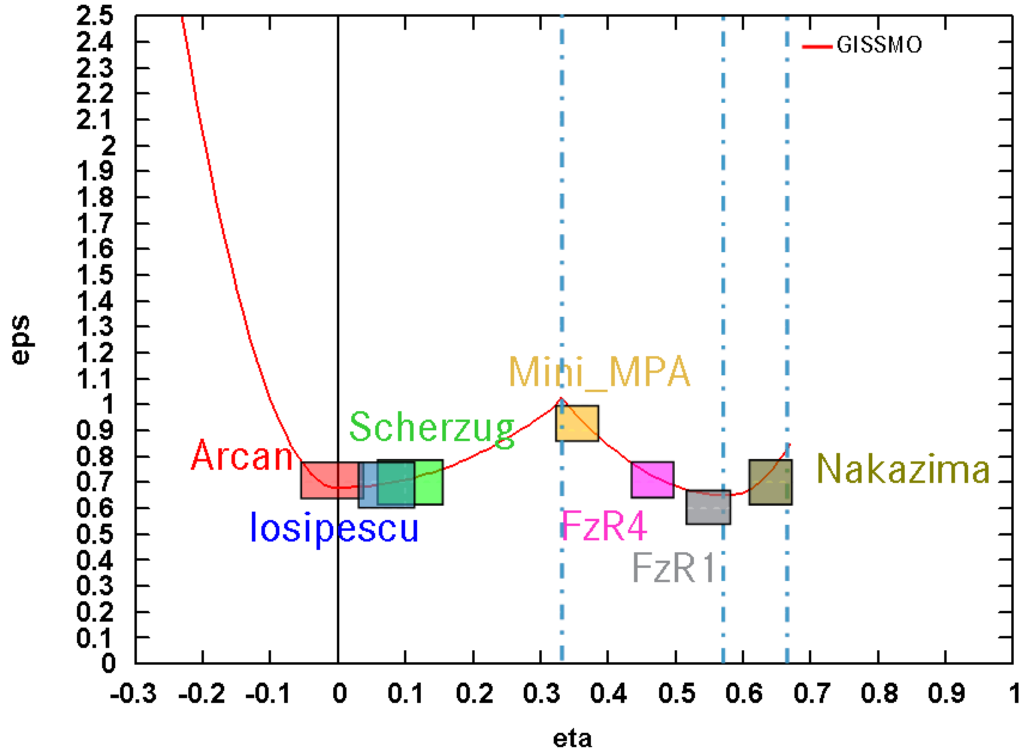

Fig. 13: Simulation results; GISSMO model

5 Summary

To improve crashworthiness simulations, it is more and more important to predict crack formation of high strength steels, for example. Several material models providing a damage evolution are available.

Two complex formulations have been introduced in this present work. On the one hand, the Gurson model with an extension of Nahshon and Hutchinson, which extends the Gurson model to consider damage evolution in shear stress states. On the other hand, a model called GISSMO, a failure criterion which uses a load curve, which can be generated from coupon tests. It can be linked with any material model.

Methods for calibrating these complex damage models have been investigated. As a result, both models are in able to describe failure depending on stress states. Calibration effort and flexibility are different for these two models.

6 Literature

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