PARAMETER IDENTIFICATION OF A DAMAGE MODEL FOR THE PROCESS CHAIN
“FORMING TO CRASH”

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Abstract
Analyzing crashworthiness of automotive parts has been a great challenge in the sheet metal and automotive industry for the last decades. Many damage/fracture models have been proposed to predict the structural failure and the developments are nowhere near the end, especially when it comes to multi-stage processes. The components to be crashed have usually pre-damage due to former processes such as forming. The pre-damage should be included in crash simulations to have better failure predictions. Moreover, the FE models used for crash simulations are usually coarser than the ones used for forming simulations, which brings out the mesh dependency problem. The GISSMO (Generalized Incremental Stress-State dependent damage Model) has features to solve the mentioned problems. The parameter identification of the GISSMO damage model and its regularization capabilities have been discussed to some extent in recent publications. Further studies have shown that the parameters identified by means of tensile tests might not necessarily provide satisfactory results for real components. Moreover, the regularization through uniaxial tensile test is not suitable for shear dominated loading, as the bending effect is not considered. This paper focuses on the parameter identification of the GISSMO damage model for different plasticity models and its further regularization capabilities. The performance of the identified parameters is also tested on side impact beam. The results show that not only the deformation but also the timing of fracture is predicted well by the parameters identified by means of the methods explained in this work.

Keywords: Process Chain, Damage, Fracture, Crashworthiness, Parameter Identification

INTRODUCTION
Predicting crashworthiness accurately starts by taking forming history into account. The importance of mapping history variables such as thicknesses and plastic strains resulting from forming processes has been shown in many publications [1]. In addition, comparison of simulations with and without consideration of local pre-damages [2] has revealed the need for a consistent damage model to be used throughout the whole process chain forming to crash. The plasticity models used in forming simulations are usually anisotropic and thereby more complex, whereas isotropic plasticity model von Mises is almost always applied for performing crash simulations. Another important distinction is the element size difference, as the crash FE models are coarser. The GISSMO damage model is flexible enough to solve these issues. However, this flexibility comes from its many parameters to be identified carefully. Inverse parameter identification methods are utilized to find out suitable values for the corresponding materials, but it can sometimes be cumbersome if the experimental data varies much.

In the current work, the parameter identification procedure explained in [3] is extended by a control variable that can reduce the influence of variation in the shear tensile test. After carefully identifying all necessary parameters for the process chain, side impact member is tested under three-point bending with two different discretizations to verify the applicability of the identified parameters and the performance of the regularization.
IDENTIFICATION OF DAMAGE PARAMETERS & REGULARIZATION

The GISSMO is a phenomenological model based on an incremental formulation for damage accumulation [4], which is expressed as

\[
\Delta D = \frac{n}{\varepsilon_f} D^{(1-1/n)} \Delta \varepsilon_v
\]

The incremental formulation enables to take different strain paths occurring in different steps of process chains into account. The nonlinearity of the damage formulation stems from the so-called damage exponent \( n \). Setting it to 1 turns it to a linear type of damage accumulation. The quantity \( \varepsilon_f \) serves as a weighting function representing the equivalent plastic strain to failure. It is given as a tabulated curve of failure strains vs. triaxiality, which is a measure of the corresponding stress state and expressed as

\[
\eta = \frac{\sigma_H}{\sigma_V} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_V}
\]

where \( \sigma_H \) and \( \sigma_V \) represent hydrostatic and equivalent von Mises stress, respectively.

The use of tabulated curve definition makes it possible not only to use the test results directly, but also to include the fracture curves obtained by different models. In this work, a fracture curve resulting from a phenomenological failure model has been utilized.

The GISSMO damage model incorporates also a path-dependent instability criterion for defining the onset of post critical range. Its formulation is similar to the formulation of damage accumulation. Instead of using tabulated curve of failure strain vs. triaxiality, the forming limit strains vs. triaxiality curve is included. If the instability measure reaches unity, coupling of the accumulated damage to stress tensor is initiated. The GISSMO damage model offers other ways to determine the strain at the onset of localization as well. Defining a scalar strain \( \varepsilon_{\text{crit}} \) or damage threshold \( D_{\text{crit}} \) are the other possibilities of defining the onset of post critical range, after which the stress reduction is achieved by means of a modified Lemaitre’s effective stress concept. The highest possible accumulated damage value is hard coded to one and represents the element failure

\[
\sigma^* = \sigma \left( 1 - \left( \frac{D - D_{\text{crit}}}{1 - D_{\text{crit}}} \right)^m \right) \quad \text{for } D \geq D_{\text{crit}}
\]

where \( m \) is the fading exponent responsible for the amount of stress reduction. It is entered as a tabulated curve of the fading exponent vs. element size in order to control the dissipated energy during element fade-out. Moreover, this regularization feature is not only available for the fading exponent but also for the triaxiality-dependent failure strain, making the GISSMO damage model suitable for multi-stage processes like forming to crash.

The following geometries covering the triaxiality range between pure shear and plain strain are selected for the identification of damage model parameters. The longitudinal direction of all specimens coincides with the rolling direction. Their force vs. displacement curves serve as experimental data for the inverse optimization process.

- Uniaxial tensile test with a gauge length of 80mm and a width of 20mm
- Notched tensile test with a notch radius of 5mm
- Shear test at 0° to the rolling direction
- Tensile test of a specimen with a hole (5mm radius)

In a recent publication [3], the identification of damage model parameters has been done solely by means of the force vs. displacement curves of the above mentioned tensile tests and their various kinds. The parameters identified in this way might provide accurate results depending on the choice elasto-plastic material model and the experimental curves as long as the experimental data has a small deviation. Otherwise, the optimized parameters would be prone to variation as well. Realizing that the experimental force vs. displacement curves
of the shear test has relatively high variation, Fig. 1, it is necessary to include a control variable in the optimization.

![Image](image1.png)

**Fig. 1** Variation of force vs. displacement curves of shear tests $0^\circ$

For this purpose the mean drawing depth of twenty square punch tests, Fig. 2, has been incorporated as a constraint in the optimization. The test results have a very small deviation making the mean drawing depth a suitable control variable for the optimization. The dimensions of the blank have been optimized in a way that all tests exhibit shear fracture. Furthermore, the friction coefficient has been adjusted according to the force vs. displacement curves. By including the mean drawing depth in the optimization, even though the resulting force vs. displacement curves might have slight differences, the optimized parameters are always in agreement with a laboratory part that can fill the gap between the tensile tests and real component tests. It should also be mentioned that including square punch simulation in the optimization means also taking into account the effect of sheet bending.

![Image](image2.png)

**Fig. 2** Square punch simulation setup (left) and critical simulation state right before fracture (right)

The identification of model parameters presumes that the yield curve and the yield locus parameters are already identified, explained in detail in [3]. Therefore, they were kept constant in the inverse identification procedure by means of LS-OPT. This leaves four parameters, namely $n$, $m$, $D_{crit}$ and scale factor of the failure strain, to be optimized for the element size 0.625mm, which is common for all tests. It was reasonable to use such a small element size due to the geometry of particularly shear test. As it can be imagined, the computation time increases considerably if the damage exponent is not an integer. Therefore, it was preferred to set it to a plausible value for the selected steel grade and to optimize the rest of the parameters. In the optimization, all four tensile tests and a square punch test were simulated at each iteration to find an optimum set of parameters by minimizing the sum of mean squared errors of the corresponding force displacement curves

$$Objective = \min \left( \sum \omega_i MSE(Tests) \right)$$

(4)

where $i$ goes up to the number of tests included in the optimization. The GISSMO damage model offers the flexibility to choose the percentage of layers to be failed before an element is removed from the FE model. In
the current work, 60% has been chosen corresponding to 3 out of 5 integration points through thickness. After each iteration, all parameter sets are checked whether they violate the constraint (5). As the number of iterations increases, both the objective function and the constraint violation are minimized.

\[
\text{Constraint} \rightarrow 0.9 \ < \ \text{damage (middle layer)@mean drawing depth} \ < \ 0.99
\]

In this work, the damage parameters were optimized for both von Mises and Yld2000-2D yield criteria. Even though the material used is slightly anisotropic, the square punch simulation has been included in the optimization of the damage parameters for von Mises yield criterion as well. As seen in Fig. 3, the resulting force vs. displacement curves capture the experimental fracture points quite good.

![Comparison of force vs. displacement curves obtained with the optimized parameters](image)

Fig. 3 Comparison of force vs. displacement curves obtained with the optimized parameters

The discretization of forming and crash steps usually differ in terms of the characteristic element length, as much coarser meshes are used in crash simulations. Hence, it is necessary to regularize the fracture curve for larger element sizes. With 20mm width, uniaxial tensile test geometry is suitable for element sizes up to 10mm. The force vs. displacement curve obtained for 0.625mm element size was used as reference for optimizing the corresponding fading exponent and scale factor. This method is called the "virtual tensile test" [5]. Due to small number of parameters, the optimization could be easily carried out by means of LS-OPT without having high computational cost. The regularization through uniaxial tensile test for both Yld2000-2D and von Mises yield criteria proves to be effective as seen in Fig. 4. The corresponding fading exponents and scale factors are also given in Fig. 5.
The regularization through uniaxial tensile test has been tested on the simulations of square punch and notched tensile test with an element size of 1.25mm, twice the one used in the optimization, to see the effectiveness under different loading conditions. It turns out that further regularization is needed under shear dominated loading, whereas no further regularization is necessary for loading under plain strain and biaxial tension. The GISSMO offers extended regularization for the mentioned loading conditions. Another parameter is used to linearly weight the regularization factors obtained through uniaxial test. The new combined regularization factor for the triaxiality range between uniaxial tension and pure shear is shown as

\[
\text{Regularization Factor} (\eta) = \left(1 - \left(\frac{\eta}{\frac{1}{3}}\right)^{\text{RegShr}}\right) \times (1 - \text{scl}) \times \text{scl} \quad 0 < \eta < \frac{1}{3}
\]  

(6)

As seen in Fig. 6, the force vs. displacement curves of the square punch simulations with different element sizes suggest that the parameter \( \text{RegShr} \) should be around 0.8 to get the same force level and the drawing depth.
To verify the applicability of the identified parameters and the regularization in a process chain, a side impact beam was chosen and tested under three-point bending. The blank was modeled by 1mm element size for the forming simulation, whereas two different element sizes, 1mm and 2mm, were used in the crash simulation. All simulations were performed using the YLD2000-2D plasticity model and the element formulation 2 (ELFORM 2) in LS-Dyna, since the same element formulation was used in the parameter identification process. The comparison of the deformation shows good agreement between the experiment and the simulations, Fig. 7. Moreover, the first element in the middle of both FE models is removed at the mean punch displacement of the experiments, at which the fracture at the same area occurs. The force vs. displacement of the crash simulation without mapping forming history shows also the importance of taking pre-straining and pre-damage into account.

The triaxiality value at the fracture location points out that the loading was between plain strain and biaxial stress states. Obtaining the same punch displacement at the time of fracture with both element sizes confirms also that the regularization through uniaxial tensile test is suitable for this type of loading condition. Although the deformation and the calculated force vs. displacement curves were in good agreement with the experiments, the edge fracture seen in Fig. 7 was not possible to realize with the identified parameters. This is highly probably due to the pre-damage occurring during cutting process of sheet blanks. The amount of pre-damage at the edges depends on the type of cutting and requires further research. Nevertheless, in order to verify the applicability of the parameters, it should be checked, whether the edge fracture influences the plastic strain accumulation of the critical elements at the fracture location in the middle. For this purpose, two rows of elements were selected and another material card with a basis fracture curve having 30% of the original fracture strain has been assigned to them. The plastic strain accumulations of the critical element in both
Simulations with and without the edge fracture are almost identical, Fig. 8, which proves that there is no influence of the edge fracture on the damage accumulation in the middle of the side impact beam.

**CONCLUSION**

In the current work, an inverse identification method for the GISSMO damage model parameters has been presented. Due to high scatter particularly in the experimental force vs. displacement curves of the shear tensile test, the optimized parameters are prone to high variation as well. In order to overcome this issue, the parameters have been identified not only by using the tensile tests but also by considering a laboratory part during the optimization. A very fine and homogeneous discretization with an element size of 0.625mm has been used for all FE models and the mesh dependent parameters have been regularized by using the uniaxial tensile test. The calculated force vs. displacement curve of the uniaxial tensile test obtained by the optimized parameters served as reference for the regularization. It was anticipated that the regularization through uniaxial tensile test might not be suitable for different loading conditions such as shear and biaxial stretching. Therefore, further regularization parameters have been introduced in the GISSMO damage model, namely $RegShr$ and $RegBiax$ [5]. Need for further regularization under shear loading has been shown utilizing the force vs. punch displacement curves of the square punch test and a better regularization for the shear area under fracture curve has been achieved with the parameter $RegShr$. It has also been demonstrated by the calculated force vs. displacement curves of the notched tensile test with two different element sizes that no further regularization is necessary for the corresponding triaxiality range. Having identified all necessary parameters, their applicability in the process chain forming to crash has been tested on side impact beam. Not only the deformation but also the timing of fracture was predicted well by the GISSMO damage model.

**LITERATURE**


