On parameter identification for the GISSMO damage model

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Abstract

In order to improve predictiveness of crashworthiness simulations, great effort has been made regarding the treatment of crack formation and propagation. To achieve this, a consistent prediction of pre-damage, accumulated during manufacturing of a sheet-metal part, can help to improve accuracy. The constitutive models used for crash simulations are usually isotropic and based on the von Mises flow rule or the Gurson, Tvergaard & Needleman approach. For forming simulations, a more sophisticated and anisotropic description of yield loci – often based on the Hill or Barlat (1989) criteria – is considered important, which makes it necessary to use different constitutive models for both parts of the process chain. A damage model suitable to be used for both disciplines therefore has to be able to correctly predict damage regardless of the details of the constitutive model formulation. To fill this gap the damage model GISSMO (Generalized Incremental Stress-State dependent damage MOdel) has been developed at Daimler and DYNAmore (Neukamm et al. (2009), Haufe et al. (2010)). It combines proven features of damage and failure description available in crashworthiness calculations with the possibility of mapping various history data from sheet metal forming to final crash loading.
The meanwhile carried out applications in everyday simulation work show excellent results based on carefully fitted material parameters. The present paper will focus on the parameter identification for the GISSMO damage model in crashworthiness simulation. A correct indication of damage and failure requires material data gained from several experimental tests. Starting from the treatment of the raw data, a procedure will be given, that shows how to calibrate the elastic-plastic behavior. In the following, a method is introduced which allows to capture damage and failure characteristics of a material. Step by step the determination and validation of particular GISSMO parameters will be discussed from a practical point of view. The objective is to give a complete overview of the calibration of a GISSMO material card.

Introduction

First of all, the fundamentals of the GISSMO damage model are summarized to get an idea of the theory behind the model. In this context the definitions of the main material parameters are given. The implied load-dependent criteria require numerous experimental coupons whose test procedures and evaluation serve as initial part of creating a well fitted material card. Based on this information a detailed description of the parameter identification follows. As the GISSMO damage model is only targeting damage and failure prediction, it does not work separately but has to be used in conjunction with a constitutive model that provides the underlying plasticity formulation. For this purpose, the widely-used *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024) was chosen in the present paper. The extraction of the yield curve is mentioned as well as the calibration of specific GISSMO values, in particular the damage and failure input parameters. Special attention is paid to the mesh-size regularization of the model in the post-critical range of deformation.

A generalized scalar Damage Model

The damage model GISSMO is a combination of proven features of failure description provided by damage models for crashworthiness calculations, together with an incremental formulation for the description of material instability and localization. A user-friendly and simple input of material parameters is intended, which is being achieved by a phenomenological formulation of ductile damage. Special attention is paid to consider the point of instability or localization, as this is a central issue in forming simulations.

Stress and strain measures

The usual notation for crashworthiness purposes is a characterization of load state using the invariants of the stress tensor. This is sufficient for isotropic material models, since the invariant notation is independent of the respective element coordinate system.
For the plane stress case, which is a common assumption for sheet metal problems (i.e. also neglecting transverse shear components), the strain increments are related to stress values by a 2D constitutive model. Furthermore, the strain-based notation of the Forming Limit Curve (FLC), which is commonly used in forming analysis, can be transformed into a notation in invariants of the stress tensor. In crashworthiness computations the notation using the stress triaxiality η is common practice:

$$\eta = \frac{\sigma_m}{\sigma_v} \tag{1}$$

with σ_m (mean stress) being the first invariant of stress tensor here given for plane stress ($\sigma_3=0$):

$$\sigma_m = \frac{\sigma_1 + \sigma_2}{3} = -p \tag{2}$$

Furthermore σ_v is the equivalent or von Mises stress:

$$\sigma_v = \sqrt{\sigma_1^{\,2} + \sigma_2^{\,2} - \sigma_1\sigma_2} \tag{3}$$

The usual way would be to compare the actual value of accumulated equivalent plastic strain to the limit value for a respective triaxiality. This corresponds to using the principal strain notation and would inherently result in the same limitations as there is no consideration of strain path changes. In general, it can be expected that stress states will usually not be the same in a metal forming process compared to a following crash loading scenario. Thus, the GISSMO model is capable to include not only the description of failure, but also the functionality to provide an incremental and therefore path-dependent treatment of instability. This is needed to avoid a limitation of the traditional FLC, which considers only the final state of deformation at the end of a forming process, and therefore does not take into account possible changes in strain path. Hence, the conventional forming limit curve can not be used for multi-stage deformation processes, as which the two steps – forming and crash – of the sheet metal process chain can be considered.

Path-dependent failure criterion

In order to allow for the treatment of arbitrary strain paths in the prediction of failure, an incremental formulation has been chosen for a damage measure D:

$$\Delta D = \frac{n}{\varepsilon_f} D^{\left(1 - 1/n\right)} \Delta \varepsilon_v \tag{4}$$

This equation represents a generalization of the well-known linear accumulation rule for damage as proposed by Johnson and Cook (1985). In this equation, the exponent n allows for a nonlinear accumulation of damage until failure. This introduces a possibility to fit the model to data of multi-stage material tests. The actual equivalent plastic strain increment is denominated as $\Delta \varepsilon_v$. The quantity ε_f represents the triaxiality-dependent failure strain, which is used as a weighting function in this relation. The input of this failure strain is realized as a tabulated curve definition of failure strain values vs. triaxiality, which allows for an arbitrary definition of triaxiality-dependent failure strains (see Figure 1). This is needed to ensure flexibility when used for a wide range of different metallic materials.

Recent publications indicate a possible nonlinearity in the relation of damage and equivalent plastic strain, even for proportional strain paths. Weck et al. (2006) performed measurements on a model material that showed a rather exponential relation between strain and damage with respect to void growth. It seems a reasonable assumption that the development of damage in metallic materials generally obeys a nonlinear relation, yet no method that would allow for a direct measurement of this quantity is known to the authors.

Path-dependent instability criterion

The basic idea is to determine the strains at the onset of localization from tests under constant stress state (proportional loading). For example, tensile tests with various notch radii, shear tests and biaxial tests can be used. The resulting forming limit curve is used as an input for the aforementioned constitutive model. Furthermore, the curve is used as weighting function for the path-dependent accumulation of necking intensity up to the expected point of instability. This method is similar to the proposal of Bai and Wierzbicki (2008). In general, the localization behavior of materials in numerical simulations depends on yield locus and evolution of the yield stress. As a direct determination of yield curves from specimen tests is not possible for the post-critical range of deformation, stress extrapolation based on engineering assumptions (or models) is used. Due to this, and as a cause of the inherent mesh-dependency of results in the post-critical range, the used parameters of an extrapolation would determine the material properties in the post-critical range, and lead to mesh-dependent results. Therefore, a damage-based regularization for the post-critical range is proposed in the present contribution. A more comprehensive description of localization issues can be found in De Borst et al. (1993).
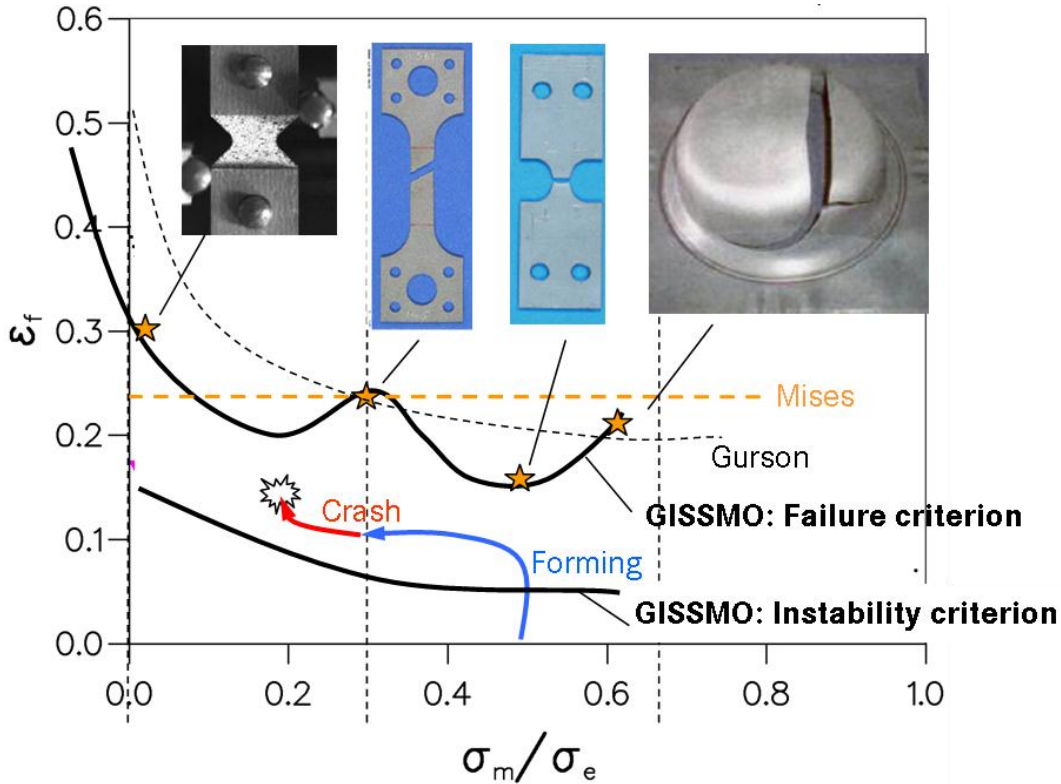
Figure 1: Tabulated input of instability and failure for GISSMO.

A nonlinear means of accumulation is introduced to the GISSMO model, using the same relation as for the accumulation of ductile damage to failure. An identification of parameters for this relation will hardly be possible from direct tests, rather by means of reverse engineering simulations of multi-stage forming processes. The introduction of an additional parameter should allow the fitting of the model to existing test data. Hence, the nonlinear accumulation

$$\Delta F = \frac{n}{\varepsilon_{v,loc}} F^{\left(1 - 1/n\right)} \Delta\varepsilon_v \tag{5}$$

is proposed which introduces the new accumulation exponent n. For $n=1$, eqn. (5) reduces to the linear form. For proportional loading, or – in general – constant values of $\varepsilon_{v,loc}$, eqn. (5) can be integrated to yield a relation between the "forming intensity" F and the eq. plastic strain:

$$F = \left(\frac{\varepsilon_v}{\varepsilon_{v,loc}}\right)^n \qquad \text{for } \varepsilon_{v,loc} = const. \tag{6}$$

For $n=1$, eqn. (6) is a linear relation of current equivalent plastic strain and equivalent plastic strain to failure. Using these relations, the forming intensity parameter F is accumulated the same way as the damage parameter D. The difference is limited to the use of a different weighting

function, which is defined as a curve of limit strain depending on triaxiality for *F*, whereas for the failure parameter *D* the fracture strain as a function of triaxiality is input.

Post-critical behavior

As soon as the forming intensity measure *F* reaches unity, a coupling of accumulated damage to the stress tensor using the effective stress concept proposed by Lemaitre (1985) is initiated. When – as an input for the accumulation of forming intensity *F* – a curve of triaxiality-dependent material instability is used this value represents the onset of material instability and therefore the end of mesh–size convergence of results. For the practical application of the model to finite element simulations with limited mesh sizes, this marks the beginning of the need for regularization of different mesh sizes. For the GISSMO model, the regularization treatment is combined with the damage model. The basic idea here is to regularize the amount of energy that is dissipated in the process of crack development and propagation. For a finite element model this results in a variation of the rate of stress reduction through element fadeout. It is achieved through a modification of Lemaitre's effective stress concept.

$$\sigma^* = \sigma(1 - D) \tag{7}$$

In combination with the treatment of material instability a damage threshold can be defined. As soon as the damage parameter *D* reaches this value damage and flow stress will be coupled. The current implementation allows for to either enter a damage threshold as a fixed input parameter or to use the damage value corresponding to the instability point. As the post-critical range of deformation is reached a value of critical damage D_{crit} is determined and used for the calculation of the effective stress tensor:

$$\sigma^* = \sigma\left(1 - \left(\frac{D - D_{crit}}{1 - D_{crit}}\right)^m\right) \qquad \text{for } D \geq D_{crit} \tag{8}$$

The fading exponent *m* which can be defined depending on the actual element size governs the rate of stress fading and thus influences directly the amount of energy that is dissipated during element fade-out.
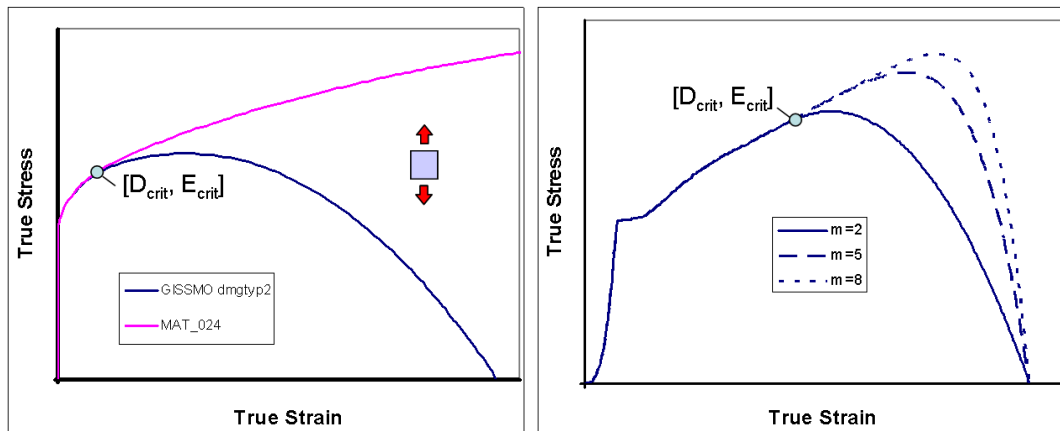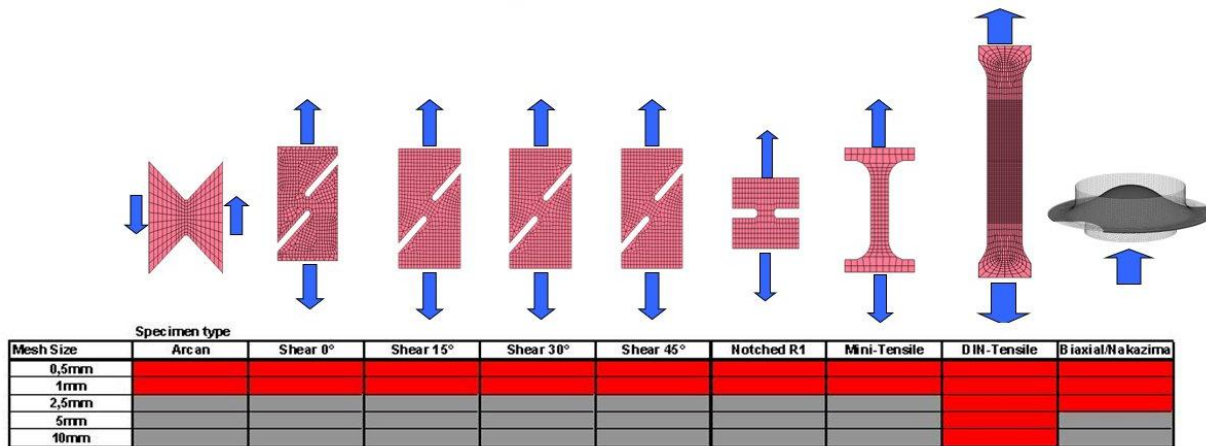

Figure 2: Coupling of the damage (left), influence of the fading exponent (right).

This strategy allows for regularizing not only fracture strains but also the energy consumed during the post-critical deformation. A reasonably good regularization of the resulting engineering stress-strain curves in tensile tests with different mesh sizes can be achieved.

Setup and Analysis of Material Tests

In the first instance information from real material tests has to be gathered. The triaxiality-dependent failure strain which makes up a principal part of the GISSMO model leads to the need for conducting experiments with different shaped specimen. In general, all load cases relevant to the considered material card have to be assessed experimentally. In Figure 3 a choice of used specimen shapes is shown.

Specimen type									
Mesh Size	Arcan	Shear 0°	Shear 15°	Shear 30°	Shear 45°	Notched R1	Mini-Tensile	DIN-Tensile	Biaxial/Nakazima
0,5mm									
1mm									
2,5mm									
5mm									
10mm									

Figure 3: Different specimen shapes and possible element sizes for discretization.

For the evaluation of the measured data all specimen have to be simulated. By using measurement of force and local displacement as in the test, a direct comparison of experiment and simulation can be achieved.

One of the most important observations coming from the simulation is that the critical elements of the computed specimen almost never follow a path of constant triaxiality during loading. Due to geometrical changes of the section over deformation, a path of varying triaxiality is followed. This effect is even more pronounced the more ductile a material is. As can be seen in Figure 4 the triaxiality measured in a critical element changes during loading for most specimen types.

This effect has to be taken into account while creating a material card, which basically means the determination of failure strain will not be a straightforward process.

Figure 4: Equivalent plastic strain vs. triaxiality in critical elements.

In this study, the following geometries were selected to create a GISSMO material card:
- Uniaxial tensile test with a parallel section
- Notched tensile test with a small notch radius
- Shear test

The experimental setups of these three tests appear quite similar, which allows for the use of a standard tensile testing machine for all of them. Clamped at both ends each specimen undergoes a displacement controlled loading at which the external tension or shear force is detected by load cells. Sensors note the translation of two points to get the displacement relative to each other. Alternatively, the elongation can be figured out by means of optical measuring techniques like ARAMIS, for example. The resulting force vs. local displacement curves can easily be converted into engineering stress vs. engineering strain curves considering the initial cross-section area of the specimen and the initial gauge length between the two observed points. After filtering and smoothing the raw data the curves serve as basis for further analyses.

The described practical procedure is reproduced within a finite element simulation. In order to represent the real physical behavior of the material the LS-DYNA® models are finely discretized using shell elements with a characteristic element length of approximately 0.5mm. The boundary conditions and the evaluation of the displacement and applied force correspond to the experimental setup.

Calibration of a GISSMO Material Card

Yield curve

In this case the plasticity is captured by the elastic-plastic constitutive model *MAT_024 considering isotropic hardening. Based on the von Mises flow rule the implied yield curve has to

be figured out from experimental results. Searching for effective stress vs. effective plastic strain the quasistatic tensile test curve can be used as reference. Since the specimen deforms uniformly before necking the engineering stress-strain curve in this part is directly converted into the effective true (or logarithmic) values:

$$\sigma_{true} = \sigma_{eng}\left(1 + \varepsilon_{eng}\right)$$

$$\varepsilon_{true} = \ln\left(1 + \varepsilon_{eng}\right), \qquad \varepsilon_{true,plast} = \varepsilon_{true} - \frac{\sigma_{true}}{E} \tag{9}$$

Beyond the point of uniform expansion the yield curve is fitted iteratively by reverse engineering. Individual or analytical approaches allow to determine the post-critical behavior until failure. The optimization tool LS-OPT® offers an efficient way for finding a suitable yield curve as discussed by Witowski et al. (2011). When using the so extracted stress-strain values, a comparison of the result of a simulated tensile test show excellent correlation with the measured test curve. As no possibility of regularizing the material model is given in *MAT_024 the curve fitting process is limited to the present mesh size.

Damage and failure

As explained above the plasticity is separately described within the material model *MAT_PIECEWISE_LINEAR_PLASTICITY. The GISSMO damage model, chosen to describe damage and failure behavior, is implemented in card 3 and card 4 of the LS-DYNA keyword *MAT_ADD_EROSION and activated by the first flag IDAM=1 (see Figure 5).

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID         RO          E         PR       SIGY       ETAN       FAIL       TDEL
        10
$        C          P       LCSS       LCSR         VP

...


*MAT_ADD_EROSION
$      MID       EXCL     MXPRES      MNEPS     EFFEPS     VOLEPS     NUMFIP        NCS
        10
$    MNPRES      SIGP1      SIGVM      MXEPS      EPSSH      SIGTH    IMPULSE     FAILTM

$      IDAM     DMGTYP      LCSDG      ECRIT     DMGEXP      DCRIT     FADEXP     LCREGD
         1          1        100       -200          2                  -300        400
$    SIZFLG      REFSZ      NAHSV      LCSRS       SHRF      BIAXF
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Figure 5: LS-DYNA input for GISSMO.

With DMGTYP=1 the damage is accumulated and element failure occurs for D=1. The coupling of the internally calculated damage to the flow stress depends on several parameters, which are identified by conducting an optimization procedure. Setting the damage exponent DMGEXP to a fixed value, the fading exponent FADEXP is obtained by LS-OPT as well as the two load curves for LCSDG and for ECRIT. The first one defines the equivalent plastic strain to failure vs. triaxiality, the second one defines the critical equivalent plastic strain vs. triaxiality.

Within the optimization loop, all three above mentioned coupon tests are computed and evaluated. The progression of each engineering stress-strain curve is compared to the experimental results aiming at a perfect correlation between both curves. Likewise the difference in the engineering failure strains is minimized. Five points with fixed triaxiality build the load curve for LCSDG where the corresponding values for equivalent plastic strain to failure are to be found by LS-OPT. The critical equivalent plastic strain represents the first occurrence of instability and therefore the start of coupling the damage to the flow stress. As necking in shear loading cases is unknown, the value in the ECRIT curve is set to an arbitrary high value, whereas the beginning of coupling for plane strain is optimized. The point of uniform expansion taken from tensile test curves delivers the critical strain for the triaxiality of uniaxial tension (i.e. 1/3). After a few iterations a fading exponent FADEXP and load curves for LCSDG and ECRIT are obtained showing very good correlations between the test and simulation data in all three calculated load cases.
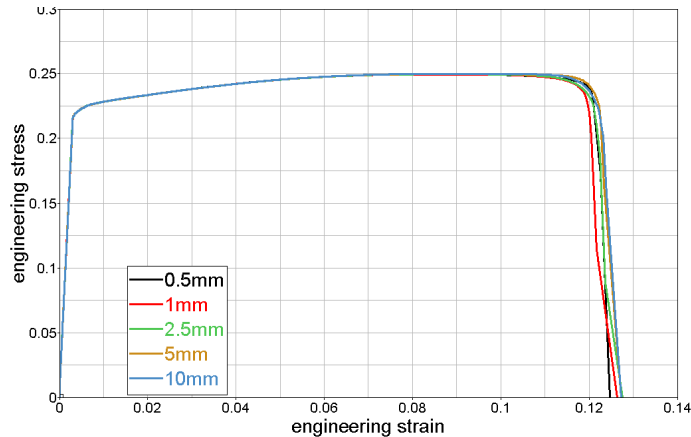
Regularization

The identified parameters are initially fitted to only one – rather small – element size (0.5mm). Due to reasons of cost-effectiveness, full-scale car crash simulations have to be done using mesh sizes far more coarse. Therefore, the need for regularizing the material card arises. For this reason a uniaxial tensile test specimen large enough for being discretized with mesh sizes >3mm has to be used for this purpose. Having a long parallel section (gauge length approximately 80mm), this specimen is simulated with all different mesh sizes considered.
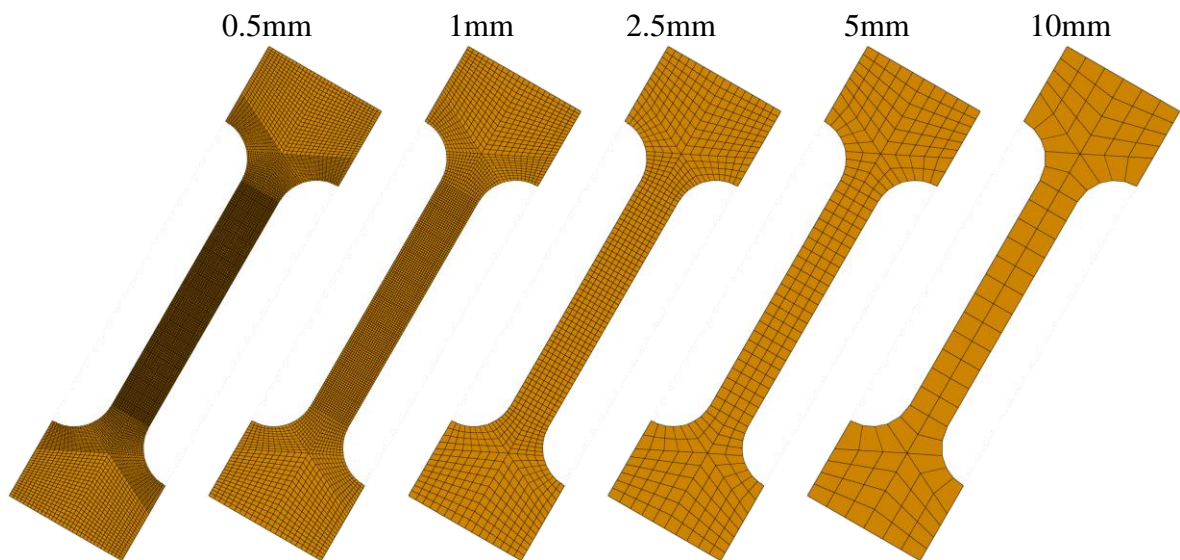
Figure 6: Differently discretized models of a tensile test specimen.

If no experimental data are available for this geometry the engineering stress-strain curve resulting from a 0.5mm mesh computation serves as reference for the validation of larger element sizes. This method is called the "virtual tensile test". The GISSMO damage model offers the possibility to regularize the fading exponent and the equivalent plastic strain to failure. With a tabulated input of FADEXP the exponent is defined in dependency of the characteristic element length. The load curve for LCREGD gives mesh-dependent factors for the failure strain load curve LCSDG with decreasing values for larger element sizes.

Figure 7: Uniaxial tensile test, regularized stress-strain curves for different element sizes.

As can be seen in Figure 7, a reasonably good regularization can be achieved using these parameters. In LS-DYNA version 971 R5 or later, two additional features were added that allow to set limits for the scaling factors at triaxiality=0 (shear, the new parameter is called SHRF) or at triaxiality=2/3 (biaxial, here the new parameter is called BIAXF). This approach is intended to further improve regularization capabilities for stress states other than uniaxial tension.

Conclusions

In the present work an effective preparation of a material card for the GISSMO damage model has been described suitable for capturing the physics of ductile damage and failure in a variety of stress states and for different materials. Some methods of numerical optimization have been introduced showing a user-friendly and simple input of material parameters. In order to improve the accuracy of specific values depending on the triaxiality more experimental tests with differently shaped specimen will have to be conducted and evaluated.

Further research work will be done concerning the calibration of the underlying plasticity model. As the yield curve is currently fitted to the uniaxial tension test the engineering stress-strain curve resulting from simulating a notched tensile test might be too soft compared to the experimental data. When damage is coupled to the flow stress and failure occurs it might not help to compensate the difference.

Another field of interest will be the correct specification of instability applying analytical approaches. Particularly with regard to higher triaxialities the identification of above mentioned reduction parameters SHRF and BIAXF will have to be investigated.

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