Energy-Based Regularization Approaches for GISSMO

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Abstract

Mesh dependence remains a significant challenge in crash simulations, particularly in modelling damage and failure. While refined meshes with element sizes of 0.5 mm are used for parameter identification, full car crash simulations require larger elements to ensure acceptable runtimes. This discrepancy in meshes leads to element size-dependent predictions for quantities like the plastic strain, necessitating regularization in damage and failure models. The material model GISSMO addresses these issues by scaling the failure strain based on stress state and element length to match reference mesh results. This paper proposes new calibration strategies for stress-state dependent regularization curves in GISSMO, focusing on shell elements and a von Mises plasticity model with isotropic hardening. The study introduces two new regularization strategies that utilize rectangular blocks of elements to achieve nearly linear strain paths for various stress states. Both strategies demonstrate promising properties, such as a monotonic decrease in failure strain across element sizes for other stress states. However, numerical noise remains a challenge. The results are validated through tensile and Nakajima tests, showing comparable quality to state-of-the-art approaches. The main advantage of the new strategies lies in their ability to regularize stress states with triaxialities from 0 to $\frac{1}{3}$, suggesting the need for further validation through component tests covering these triaxialities.

1 Introduction

Despite the increase in computational power and the ability to parallelize across multiple cores, mesh dependence still is an important issue in crash simulations, especially when damage and failure occur. While parameter identification for material models can use refined meshes with 0.5 mm element sizes, full car crash simulations require larger elements due to runtime limitations. Typical meshes consist of shell elements that range from 3 to 5 mm. Geometrical deviations between the FE mesh and the actual geometry can occur, especially at sharp notches and holes. This results in mesh-size-dependent predictions for quantities such as plastic strain and damage. Therefore, material parameters calibrated on a fine mesh cannot be used directly on a coarse mesh, and regularization is necessary. In the GISSMO material model, the failure strain is reduced by a scale factor, which depends on the element size and current stress state. This allows comparable stress-strain curves to be achieved for different element sizes in a tensile test, for instance. This publication proposes new calibration strategies for stress-state-dependent regularization curves in GISSMO. The study is limited to shell elements and a von Mises plasticity model with isotropic hardening.

2 Damage and failure modelling in crash simulations

2.1 GISSMO

The damage and failure model GISSMO is widely used in crash simulations to model damage and failure in metallic materials. It is available via **`*MAT_ADD_DAMAGE_GISSMO`** in LS-DYNA. In GISSMO, the scalar damage variable D is incrementally accumulated with a damage increment $\Delta D = \frac{n}{\varepsilon_{\mathrm{f}}(\eta)} D^{1-\frac{1}{n}} \Delta\varepsilon_{\mathrm{p}}^{\mathrm{v}}$ in each time step. The damage increment is proportional to the plastic strain increment $\Delta\varepsilon_{\mathrm{p}}^{\mathrm{v}}$. Additionally, ΔD depends on prior damage via the damage exponent n and the stress state described by the failure strain $\varepsilon_{\mathrm{f}}(\eta)$. For shell elements, the stress-state can be parametrized using triaxiality $\eta = \frac{1}{3}\frac{\mathrm{tr}(\boldsymbol{\sigma})}{\sigma_{\mathrm{vM}}}$, where $\mathrm{tr}(\boldsymbol{\sigma})$ is the trace of the stress tensor and σ_{vM} is the von Mises stress. A variety of tensile tests with different specimen geometries, punch tests, and possibly bending tests are performed to calibrate $\varepsilon_{\mathrm{f}}(\eta)$. Then, $\varepsilon_{\mathrm{f}}(\eta)$ is optimized, so that the simulation results match those of the physical tests. GISSMO can be used in an uncoupled or a coupled formulation in which damage reduces the components of the stress tensor. Only the uncoupled formulation is considered in the following.

2.2 The regularization problem

Without regularization, different meshes yield different results, as can easily be seen in a tensile test. Because the localization zone is small, coarse meshes cannot capture the plastic strains correctly. Using the same failure strain across all element sizes results in deviations in the stress-strain curves, with later failure and higher stresses after necking for larger elements. To ensure comparable results for different mesh sizes, GISSMO implements a regularization scheme. The failure strain $\varepsilon_{\mathrm{f}}(\eta)$ is scaled by a regularization factor $LCREGD(\eta, \ell)$, which depends on the stress state and the element size. In effect, a distinguished failure curve can be set for every element size. The failure curve for large element sizes can be determined using virtual experiments, i.e. by comparing their simulation results to the results produced by a fine mesh. The stress state dependence can be based on predefined curve shapes using $BIAXF$ and $SHRF$ or $RGTR1$ and $RGTR2$, or it can be freely defined using a table with triaxiality and element size as the independent quantities. This leads to various regularization approaches. In this publication, two state-of-the-art approaches using $BIAXF$ and $SHRF$ as well as $RGTR1$ and $RGTR2$ and two new approaches for a freely defined stress-state dependence are considered. Regularization performance is evaluated using tensile and Nakajima tests with different triaxialities. The specimen geometries are shown in Fig. 1.

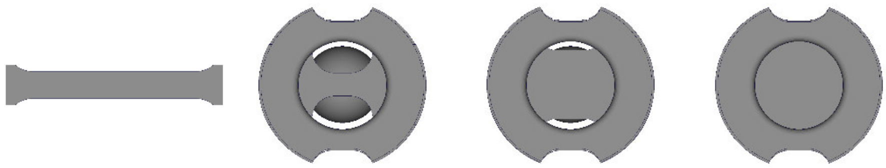

Fig.1: Tensile and Nakajima geometries

3 Regularization approaches with prescribed stress-state-dependence

3.1 Approach 1: BIAXF & SHRF

Using BIAX and SHRF, a bilinear curve for the regularization factor depending on triaxiality is assumed. The set points are shear ($\eta = 0$), uniaxial tension ($\eta = \frac{1}{3}$) and biaxial tension ($\eta = \frac{2}{3}$). In uniaxial tension, localization through necking occurs, necessitating regularization. In shear and biaxial tension, no localization is expected, and regularization is not needed, corresponding to $BIAXF = 1$ and $SHRF = 1$. However, to ensure failure in stress states such as plastic plane strain with $\eta = \frac{1}{\sqrt{3}}$ often full regularization in biaxial tension is assumed instead and $BIAXF = 0$ is used. This regularization approach is considered here. The regularization factor is calibrated using a tensile test with different mesh sizes. The factors are optimized for each element size until the stress-strain curves match the reference stress-strain curve. The resulting failure curve and simulation results for tensile and Nakajima tests are shown in Fig. 2 for a 6000 series aluminum. The tensile test results are similar for all meshes, but the biaxial punch test results vary considerably.

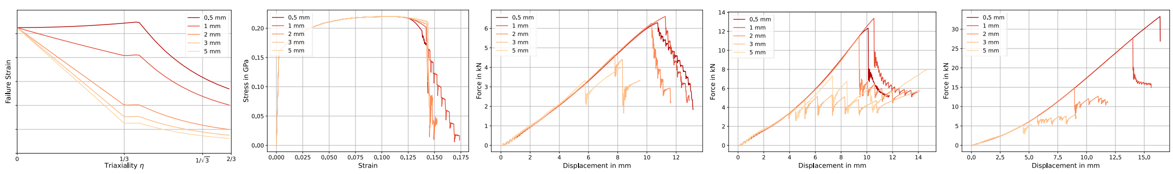

Fig.2: Regularization with BIAXF=0 and SHRF=1. Failure curve, tensile test, Nakajima 15 mm, Nakajima 45 mm and Nakajima 85 mm

3.2 Approach 2: RGTR1 & RGTR2

The second approach employs a trilinear regularization curve. Two triaxialities, $RGTR1$ and $RGTR2$, are defined to limit the range of full regularization. In combination with $SHRF = 1$ and $BIAXF = 1$, no regularization is applied in shear and biaxial tension. Calibration is again performed on a tensile test with different element sizes. The results for this approach are shown in Fig. 3. There is a clear improvement in biaxial tension over the use of the bilinear curve with $BIAXF = 0$, without losing predictive accuracy for the other tests.

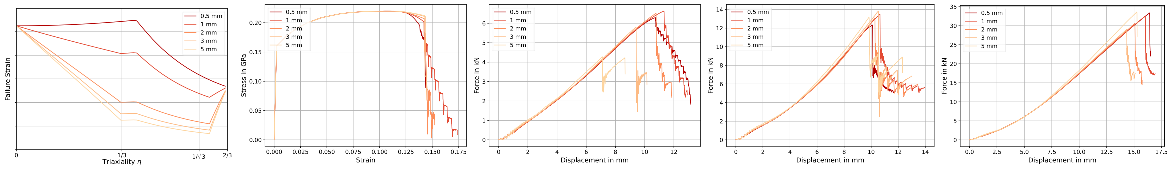

Fig.3: Regularization with RGTR1=0.33 and RGTR2=0.61. Failure curve, tensile test, Nakajima 15 mm, Nakajima 45 mm and Nakajima 85 mm

4 Energy-based regularization approaches

4.1 Imposing constant triaxialities on element blocks

There are some limitations to using bi- and trilinear regularization curves and calibrating with a tensile test. First, a tensile test always shows a nonlinear strain path that starts at $\eta = \frac{1}{3}$ and moves towards $\eta = \frac{1}{\sqrt{3}}$. This means that several stress states influence the regularization factor. Second, the tensile test only covers a limited range of stress states. No information is available for stress states from $\eta = 0$ to $\eta = \frac{1}{3}$. When such stress states occur, for instance in component tests, increased deviations between fine and coarse meshes are possible. Two new regularization approaches are proposed to address these issues. Based on [1], rectangular element blocks are loaded with displacement and force boundary conditions that produce constant triaxialities. This allows strain paths to remain linear up to high plastic strains for arbitrary stress states. To use these element blocks in regularization, triaxialities between $\eta = 0$ and $\eta = \frac{2}{3}$ in discretization steps of 0.01 are imposed.

4.2 Approach 3: Blockwise equivalent energy approach

In the blockwise equivalent energy approach, blocks with an equal size of 40x40 mm are meshed with element sizes of 0.5 (reference size), 1, 2, 3 and 5 mm. For each stress state, the internal energy at failure is evaluated, allowing for the construction of a triaxiality-dependent energy curve. The larger the element size, the higher the energy value for each triaxiality. Regularization factors can be calculated by dividing the energies for each element size by the energy of the reference element size. Repeating this procedure iteratively until convergence yields a regularization curve as shown in Fig. 4. The resulting failure curves exhibit promising properties, such as monotonic decrease across element sizes, and the same failure strains are observed for all element sizes in both biaxial tension and shear. However, due to the iterative nature of the calibration procedure and the number of stress states considered, calibration is computation-intensive.

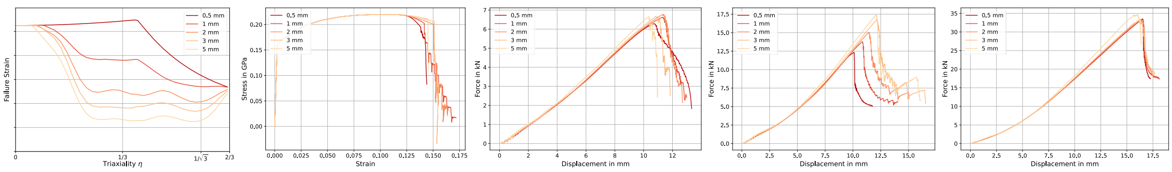

Fig.4: Regularization with BIAXF=0 and SHRF=1. Failure curve, tensile test, Nakajima 15 mm, Nakajima 45 mm and Nakajima 85 mm

4.3 Approach 4: Elementwise equivalent energy approach

The elementwise equivalent energy approach also builds on blocks with constant triaxiality. However, unlike the first approach, the block size is reduced so that a single 5x5 mm element is compared to a 10x10 element block with 0.5x0.5 mm edges. This decreases calculation time for each stress state and allows direct calibration of failure strain per state. At the time of failure in the block of small elements for every stress state, the plastic strain in the single large element is evaluated. This strain is then used as the failure strain for the corresponding stress state, which directly yields failure curves. Compared to the first approach, there is increased numerical noise, which can cause a loss of monotonicity across element size. Nevertheless, the overall results show plausible behavior and have positive attributes, such as the same failure strains for all element sizes in biaxial tension and shear.

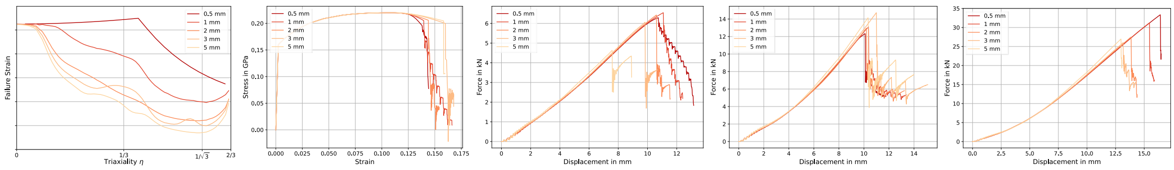

Fig.5: Regularization with BIAXF=0 and SHRF=1. Failure curve, tensile test, Nakajima 15 mm, Nakajima 45 mm and Nakajima 85 mm

5 Application for different materials

To evaluate the four regularization approaches, each approach is applied to three materials, a 6000 series aluminum, a low strength steel and a high strength steel. These materials vary strongly in their mechanical properties, i.e. maximum tensile strength and failure strain, and consequently in their hardening characteristics and their GISSMO failure curves. For each element size and each regularization approach, an error is calculated based on energies $error = \frac{|energy - energy_{0.5mm}|}{energy_{0.5mm}}$, where energy refers to the integral of force over displacement. The errors are then averaged across the Nakajima and tensile specimens. Fig. 6 shows the results for the three materials. The errors depend strongly on the material properties. The error magnitude is much larger for the high strength steel than for the other materials. Still, some differences between the regularization approaches can be seen across all materials. Using $BIAXF = 0$ and $SHRF = 1$, the average error is always high, mostly caused by the biaxial Nakajima specimen. The lowest errors are achieved by the $RGTR1$ and $RGTR2$ approach. Both equivalent energy approaches perform similar with errors mostly in between these two approaches.

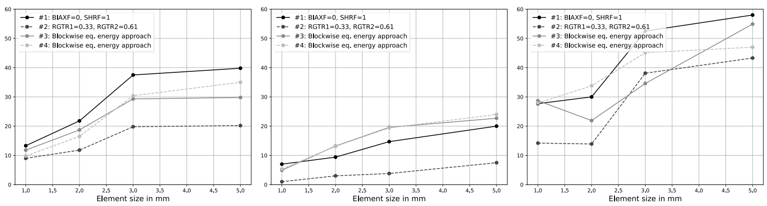

Fig.6: Application of regularization approaches. From left to right: 6000 series aluminum, low strength steel, high strength steel

6 Conclusion

Two new energy-based regularization strategies have been proposed that allow calibration of regularization curves for arbitrary stress states in shell elements. Using rectangular blocks of elements allows for nearly linear strain paths for every stress state. The resulting failure curves have desirable properties: they reach the same failure strain for every mesh size in shear and in biaxial tension, and they exhibit a monotonically decreasing failure strain across element sizes for all stress states in between. However, numerical noise can interfere with these properties. The results of the new regularization approaches are of similar quality as state-of-the-art approaches with a prescribed stress-state dependence in tensile and Nakajima tests. The results depend heavily on the specimen geometry and the material in question. The main benefit of the new regularization strategies is their ability to allow regularization in stress states with triaxialities ranging from $\eta = 0$ to $\eta = \frac{1}{3}$. Consequently, additional validation should be performed by simulating a component test that covers these triaxialities with different mesh sizes.

7 Literature

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[2] LS-DYNA Keyword User's Manual Volume II, R12, Livermore Software Technology, 2020