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Increasing predictability in crashworthiness simulation: pushing the limits

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Overview

- Failure models in LS-DYNA : GISSMO
- Localisation and regularisation
- Strong anisotropic flow and damage
- Summary and conclusions

predicting failure is far more difficult than predicting ductile deformation
J. Jergeus, 2012

Failure models in LS-DYNA

Introduction

- Many material and failure models available in LS-DYNA
- Every failure and material model should be as complicated as necessary and as simple as possible
- Adapted to the needs of a specific user community
- Will also inevitably reflect the experience of the development team
- Classical material science theory aims for a predictive analytical model based upon as few parameters (=tests) as possible
- This seems an elusive goal
- Many modern material and failure models are tabulated
- The basic idea is to assemble as many tests results as possible, tabulate them and interpolate between the tabulated values in the application
- Both approaches have a limited range of validity

Elements of failure models

- Damage accumulation : usually (but not always) based on plastic strain, can be linear or non-linear, scalar or tensorial, isotropic or anisotropic etc….
- Damage coupling : reduction of material stiffness and strength prior to failure
- Failure criterion : function of state of stress, temperature, strain rate…
- Regularisation : one of many methods
- Discretisation of failure : element erosion, constrained nodes, ALE, meshless methods, XFEM, isogeometric methods …

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Examples of recently added failure models in LS-DYNA

	developer	User community	Coupled damage	Temp. dependent	regularisation	Damage mapping
GISSMO	Daimler DYNAmore	crash	optional	no	Load curve	yes
MAT_224	FAA/NCAC LSTC	aeronautical	no	yes	Load curve	no
MAT_107	NANTUA LSTC	ballistics	yes	yes	viscosity	no
MAT_037	GM LSTC	forming	no	no	none	no

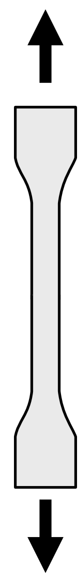
First 3 models draw heavily on the original work of Johnson and Cook

Notions in failure and instability theories

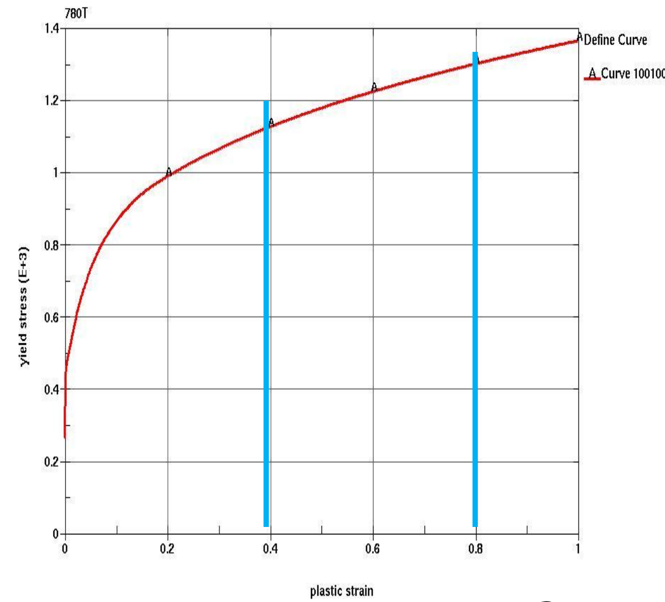
Diffuse necking : the point where we observe a loss of the homogeneous state of deformation, a pretty CLEAR notion, at least at the simulation level

Local necking : basically the formability limit, a rather FUZZY notion that needs to be defined for every application, can depend on the size of the imperfection and the size of the grid (numerical or DIC)

Failure : the point where a simply connected part becomes multiply connected : cracks appear, also a pretty CLEAR notion



$$\sigma_y = k\varepsilon_p^n$$



$\varepsilon_p = n$ *diffuse*

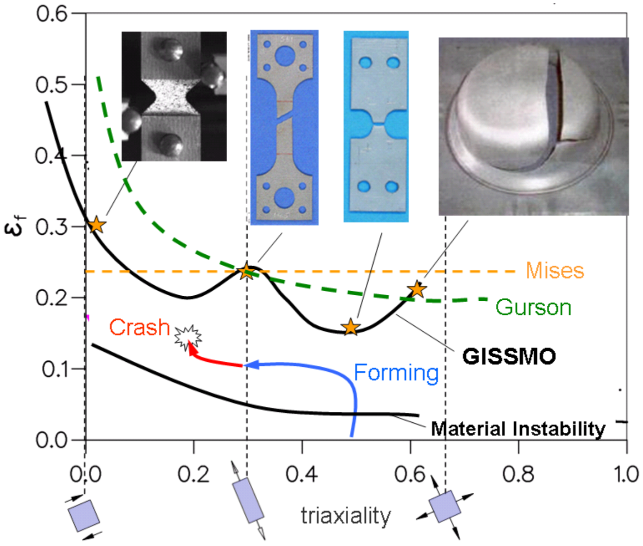
$\varepsilon_p = 2n$ *local*

The philosophy of GISSMO

The user defines a failure curve (the onset of cracks) and
a critical strain curve (the loss of uniformity in the strain field)

Between the critical strain curve and the failure curve
we assume a continuous process of localisation
inducing mesh dependency, this process
corresponds to some combination of damage
and plastic instability :

$$plasticity \Rightarrow \begin{Bmatrix} damage \Rightarrow instability \\ instability \Rightarrow damage \end{Bmatrix} \Rightarrow failure$$



If the failure curve is reached before the critical
strain curve we assume a ‚brittle‘ failure not
preceded by localisation and damage : $plasticity \Rightarrow failure$

The philosophy of GISSMO

The critical strain curve can be considere as :

onset of diffuse necking

start of localisation of plastic deformation

start of mesh dependency

start of a need for regularisation

start of damage coupling

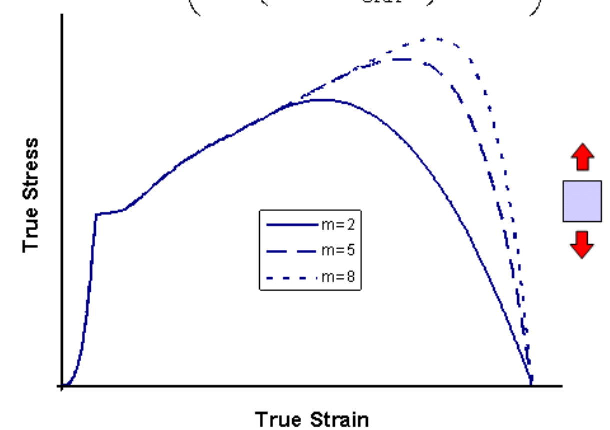
The fading exponent in the damage coupling constitutes another element of the regularisation procedure

Damage evolution

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

Damage/stress coupling

$$\sigma^* = \sigma \left(1 - \left(\frac{D - D_{CRIT}}{1 - D_{CRIT}}\right)^{FADEXP}\right)$$



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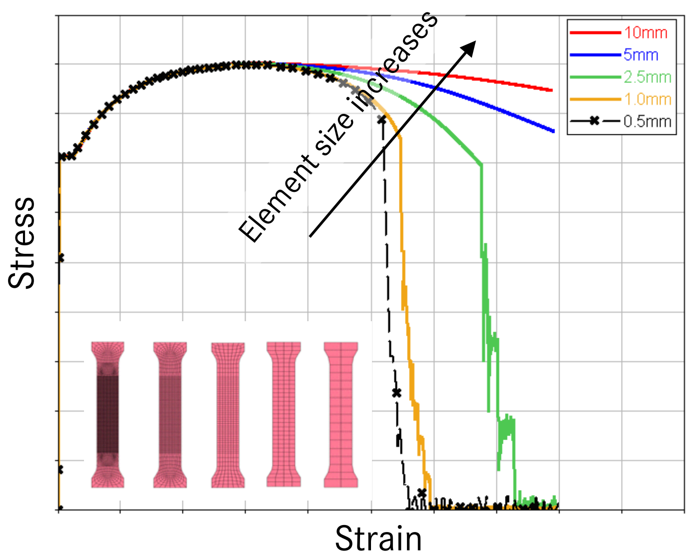
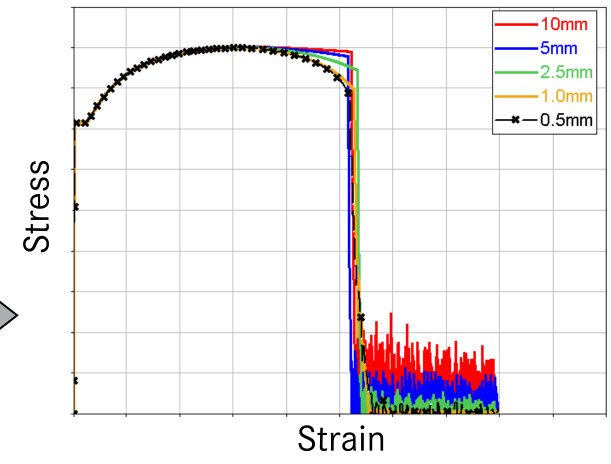
Regularisation in GISSMO

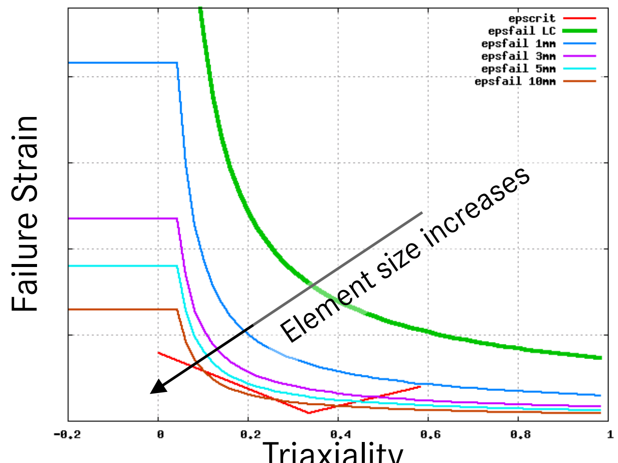
Mesh size dependency



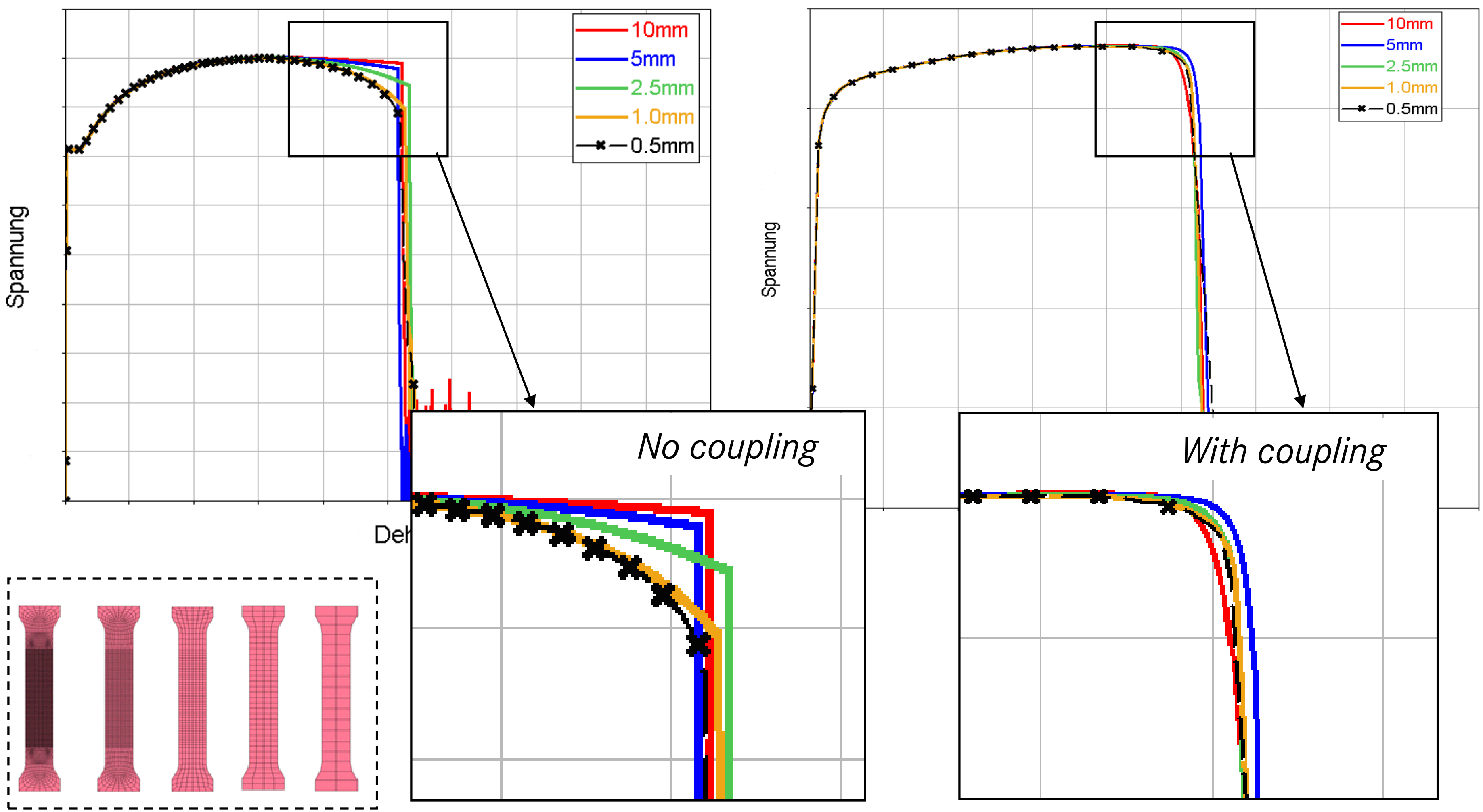
- Inherent mesh-size dependency of results in the post-critical region
- Simulation (and calibration) of tensile test specimen with different mesh sizes

Simple regularization





Regularisation in GISSMO



Small differences in force levels can imply high differences in crack propagation speed

The philosophy of GISSMO : the mapping aspect

F2C is essential for all cold formed components

Use of material laws is very different in the forming and crash communities

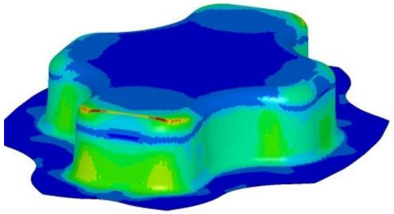
Hill	Barlat	others
37, 39, 122, 125 103, 104, 243	33, 36, 133, 190 242, 226	135, 244, 233 136, 113

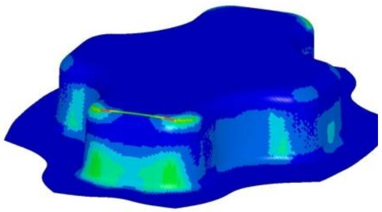
⇒

MAT_024
MAT_XXX

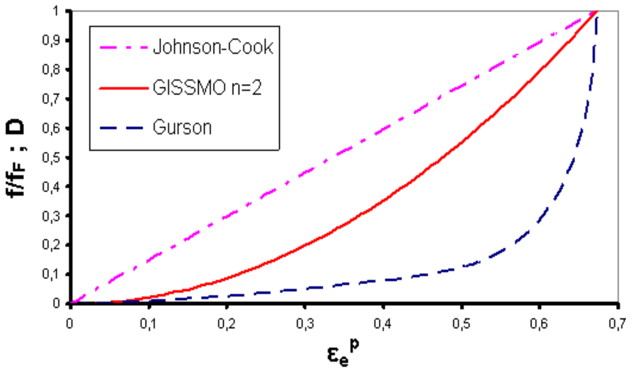
A flexible implementation of the failure/damage model as *MAT_ADD is necessary

In order not to overestimate the mapped damage at the end of the forming simulation, the damage evolution must be non-linear





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



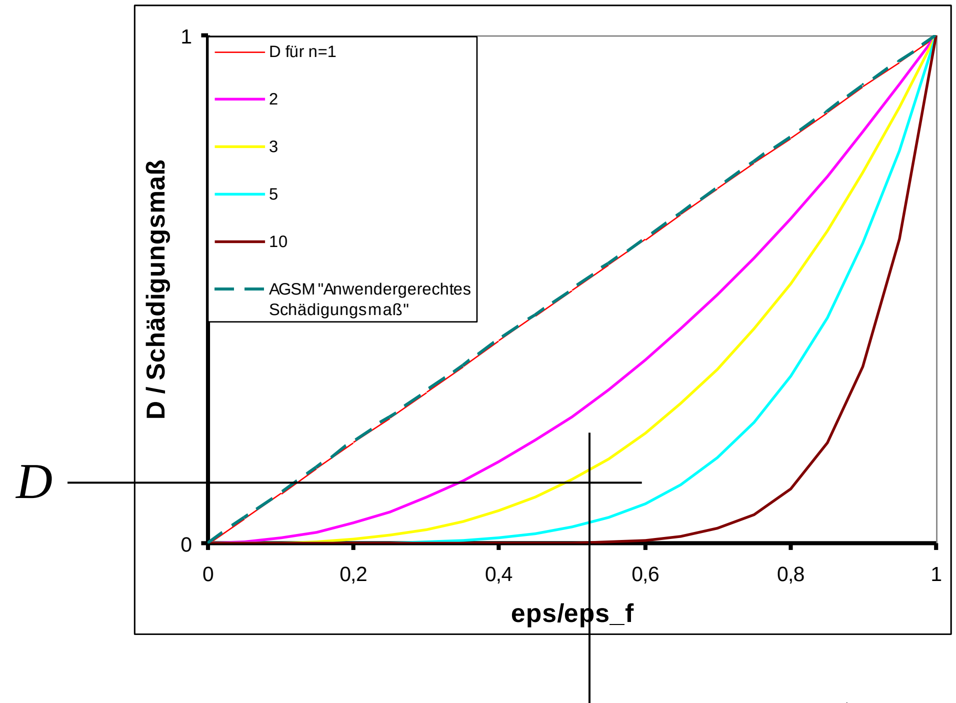
Linearized measure of damage for GISSMO

Damage evolution in GISSMO :

$$D = \left(\frac{\varepsilon_p}{\varepsilon_f}\right)^n \Bigg|_{\varepsilon_f = const}$$

$$\dot{D}(\varepsilon_p) = \frac{n}{\varepsilon_f}\left(\frac{\varepsilon_p}{\varepsilon_f}\right)^{n-1} \dot{\varepsilon}_p \Bigg|_{\varepsilon_f = const}$$

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

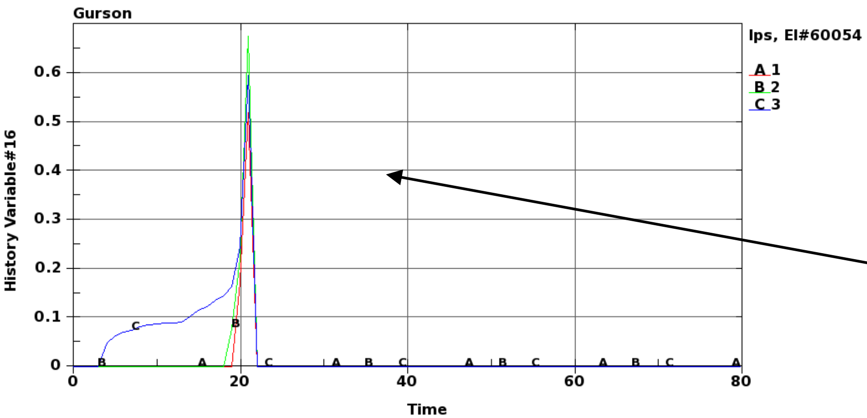


AGSM = equivalent plastic strain over failure strain at current triaxiality

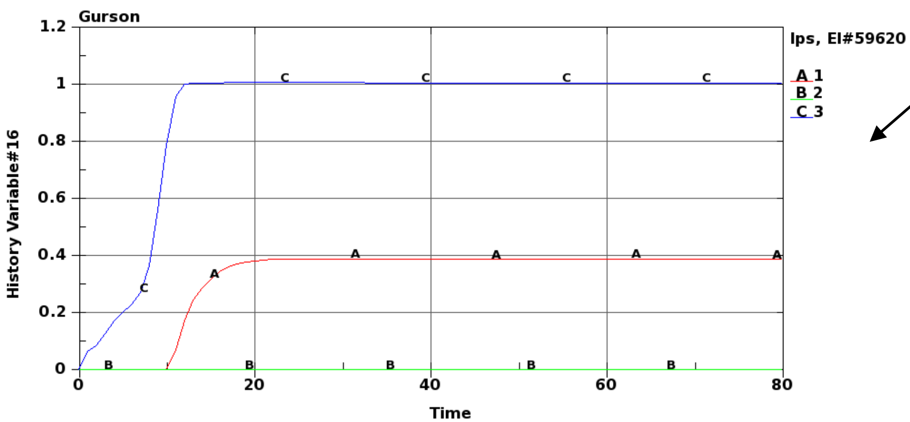
$$AGSM = D^{\frac{1}{n}}$$

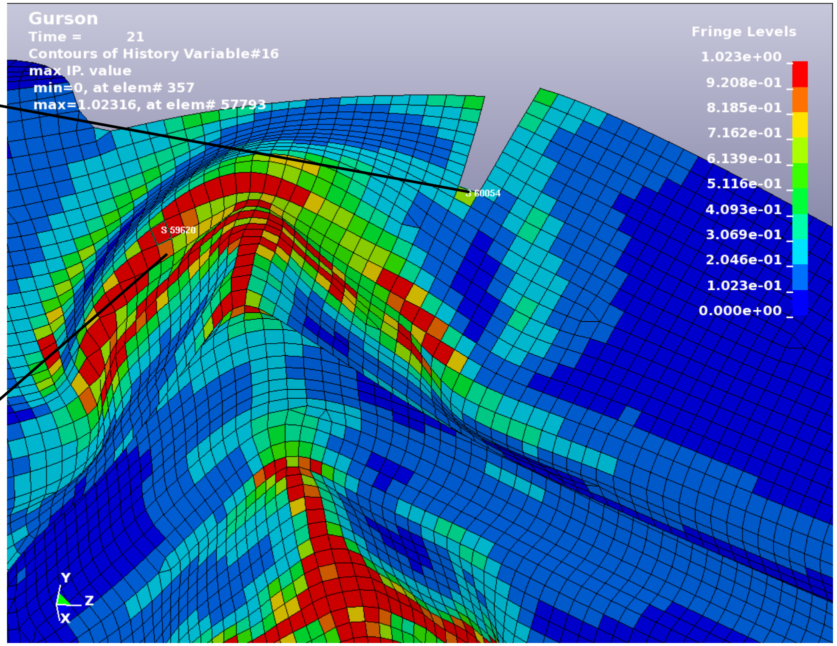
$$AGSM = \frac{\varepsilon_p}{\varepsilon_f}\Bigg|_{\varepsilon_f = const}$$

Example of a component test with failure



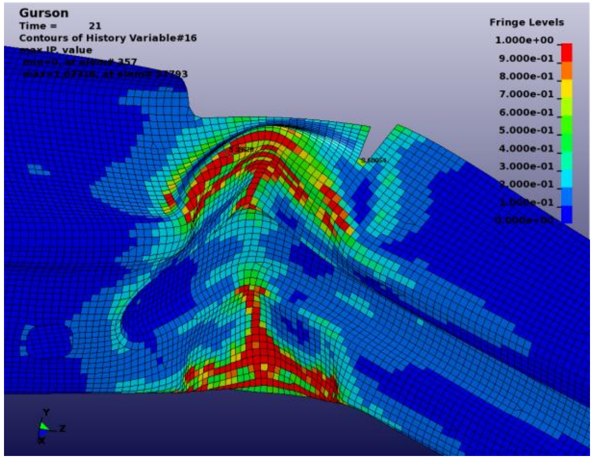
Linearized damage = HV16



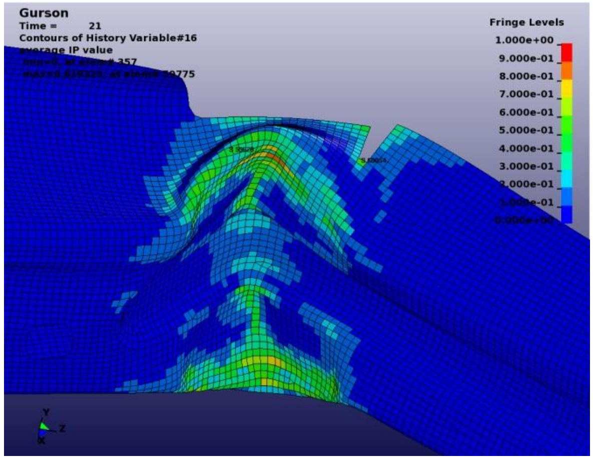


Fringeplot based on max IP is not reliable

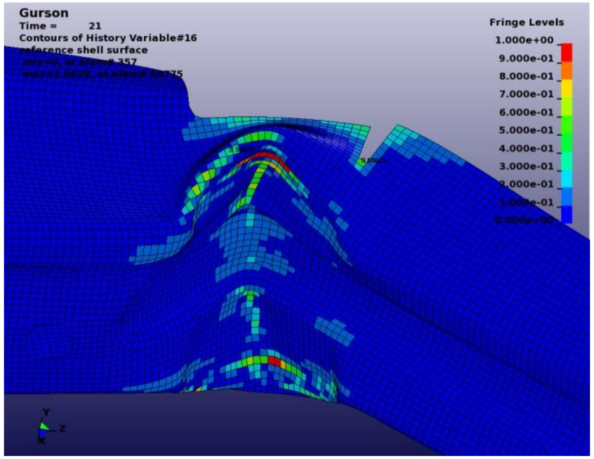
Postprocessing of the linearized damage



AGSM „max. IP“



AGSM „average“



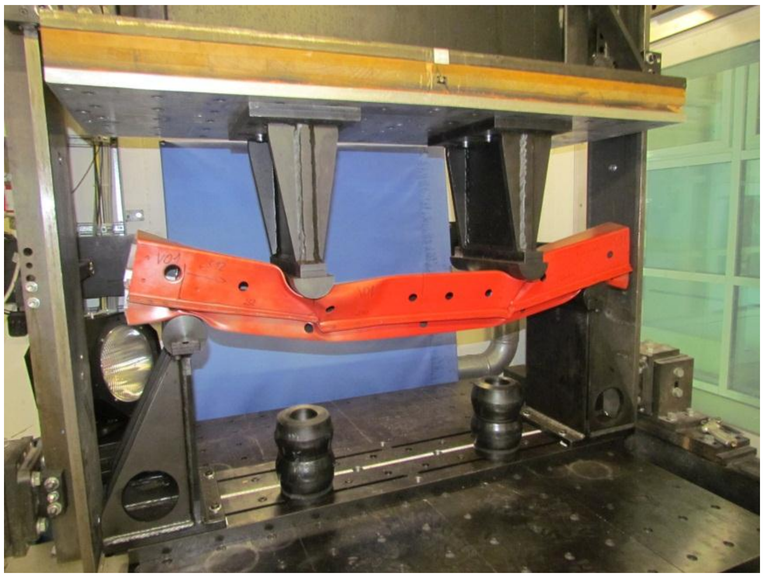
AGSM „IP1=MID“

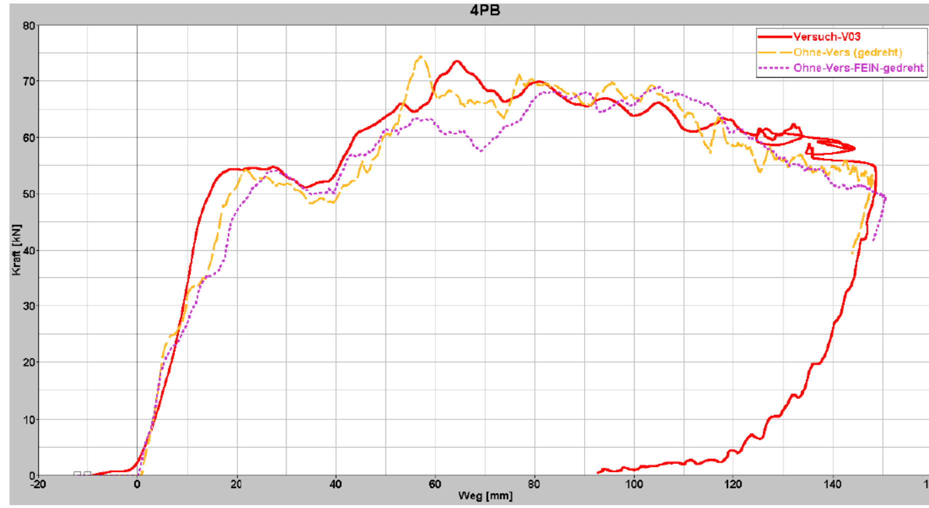
$\Rightarrow$ there is really no ‚early warning‘ system for failure

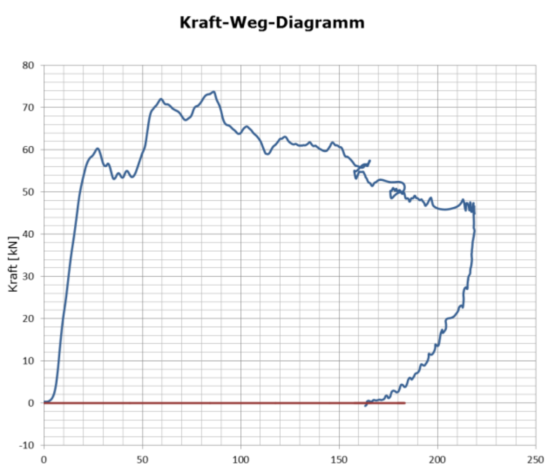
Localisation and regularisation

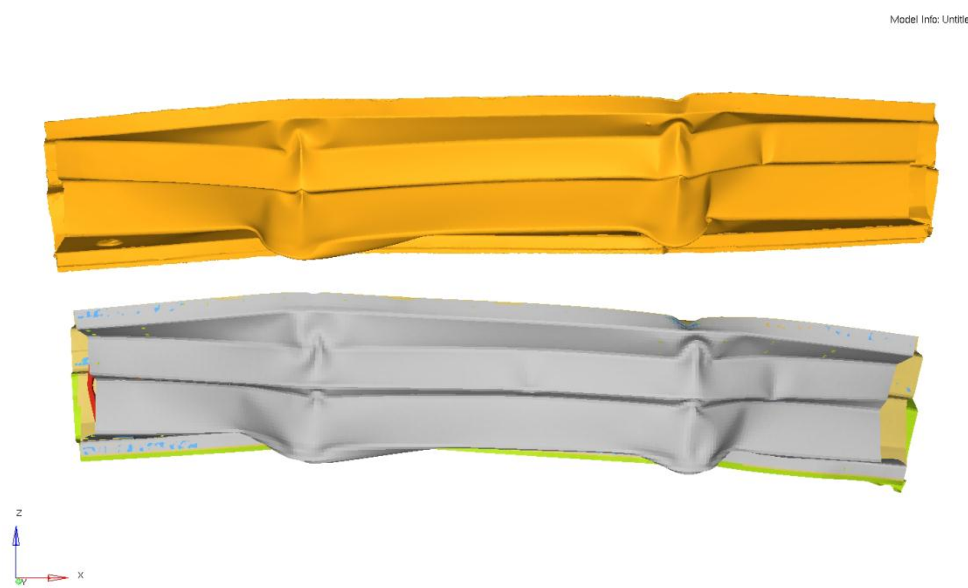
State of the art in vehicle component modelling

4PB test



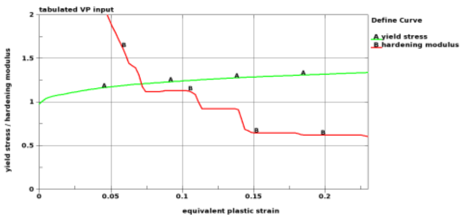


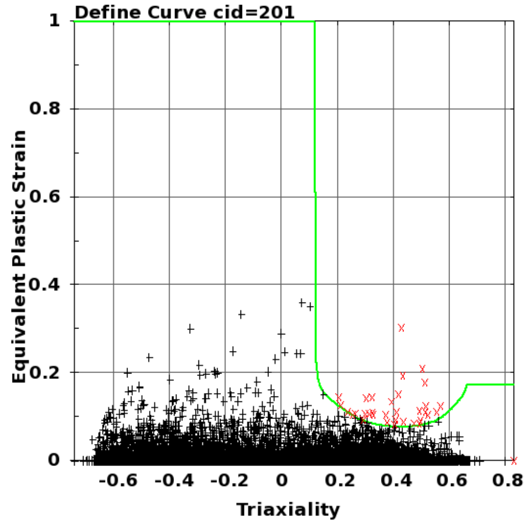


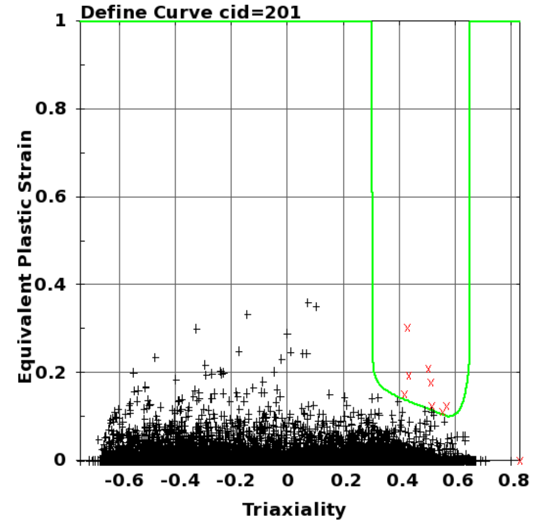


State of the art in vehicle component modelling

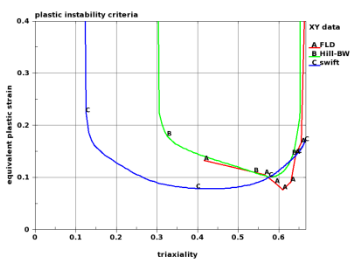
4pb 5mm

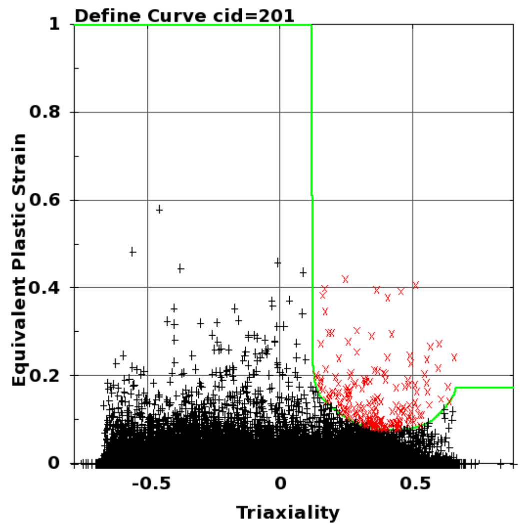


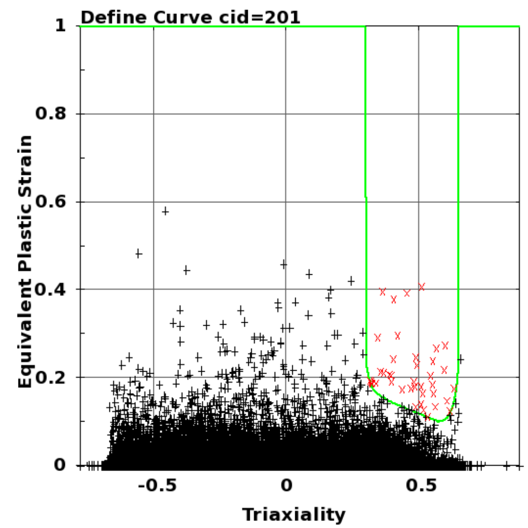




4pb 2.5mm







observations

- Convergence in terms of displacement and force does not necessarily inly convergence in terms of stress and strain
- Failure models without regularisation cannot work on non-homogeneous meshes as failure will be biased towards the smaller elements

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Localisation of plastic deformation

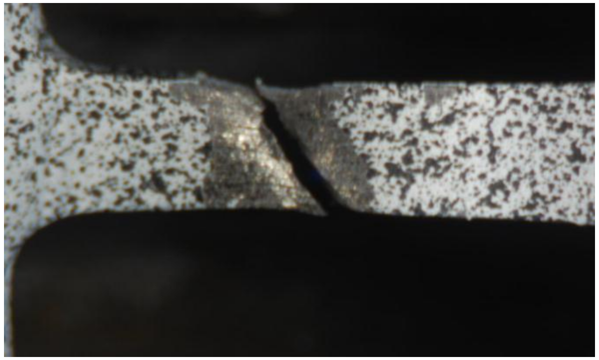
- Localisation comes with instability : $k = \frac{\partial f}{\partial d} < 0$
- Two kinds of instability as : $f = \sigma A$
- Structural instability : (e.g. necking)

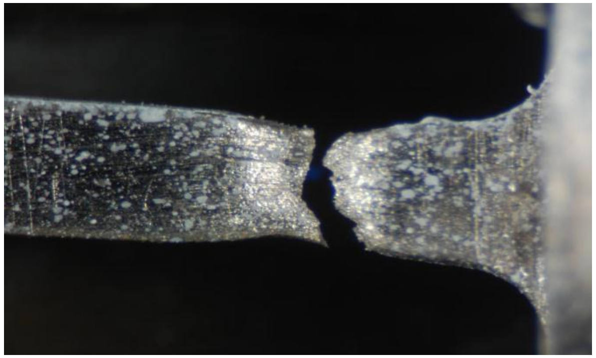
$$\frac{\partial A}{\partial d} < 0 \quad \frac{\partial \sigma}{\partial d} > 0$$

- Material instability : (e.g. shearband)

$$\frac{\partial A}{\partial d} \geq 0 \quad \frac{\partial \sigma}{\partial d} < 0$$

- Any instability will require regularisation





Types of material instability

- Decrease of stress with increase in strain :
- Strain softening : (not in metals) $$\frac{\partial \sigma}{\partial \varepsilon} < 0$$
- Rate softening : (PLC effects) $$\frac{\partial \sigma}{\partial \dot{\varepsilon}} < 0$$
- Thermal softening : (adiabatic shearbands) $$\frac{\partial \sigma}{\partial T} < 0$$
- No instability is expected in metals under QS isothermal shear loads, so no regularisation should be necessary
- Onset of instability in general depends upon many factors

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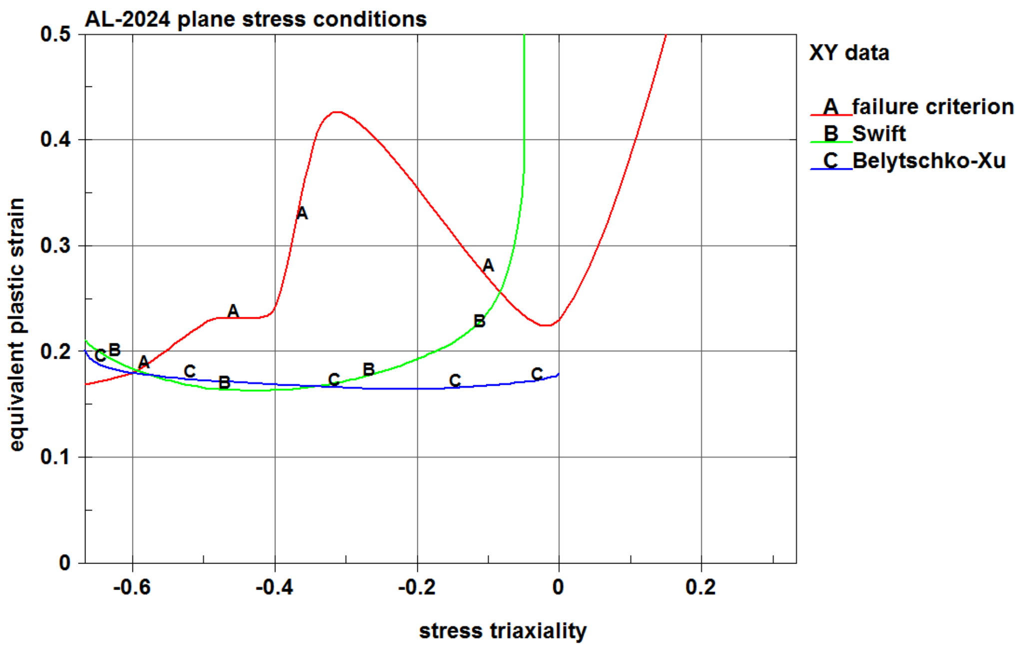
Methods to identify the onset of localisation



Example of the Swift

$$\frac{\partial \sigma_{vm}}{\partial \varepsilon_p} = \sigma_{vm} \frac{(2-a)^2 + (2a-1)^2 a}{4\sqrt{(1-a+a^2)^3}}$$

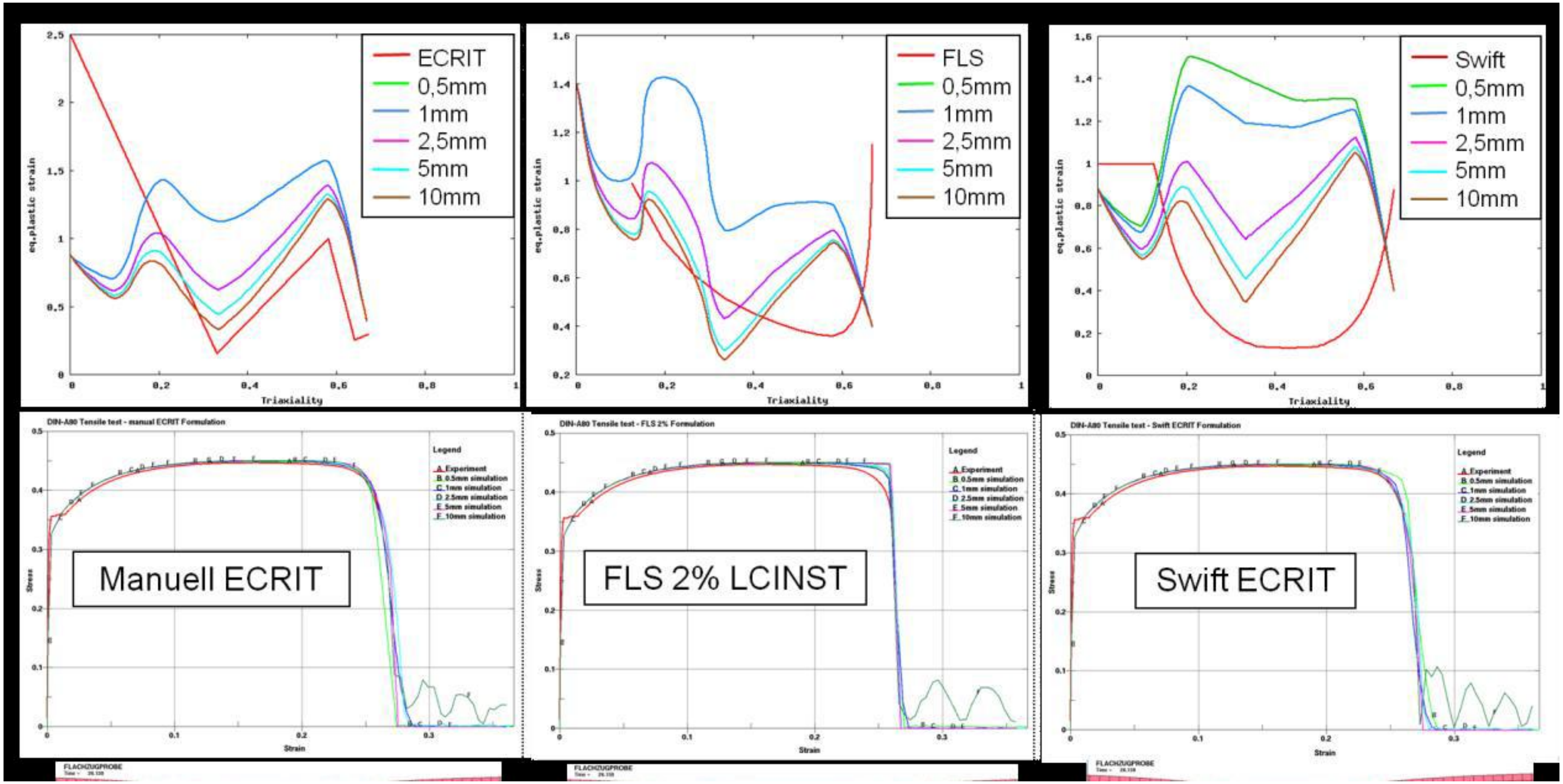
versus Belytschko

$$\frac{\partial \sigma_{vm}}{\partial \varepsilon_p} = \sigma_{vm} \cos\left(\frac{\pi}{6} - \frac{1}{3} a \sin\left(-\frac{(2-a)(2a-1)(a+1)}{2\sqrt{(1+a^2-a)^2}}\right)\right)$$

criterion for AL-2024

Different criteria do exist !

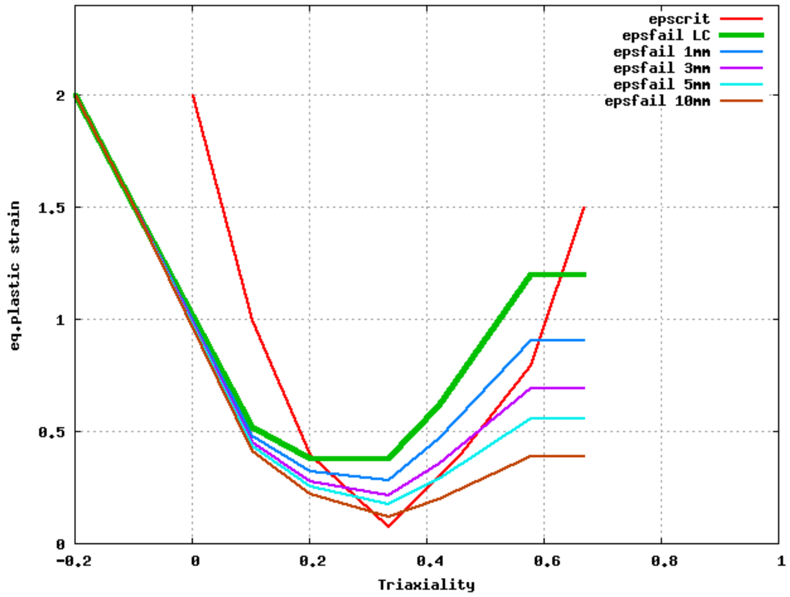
Different assumptions for ECRIT in GISSMO



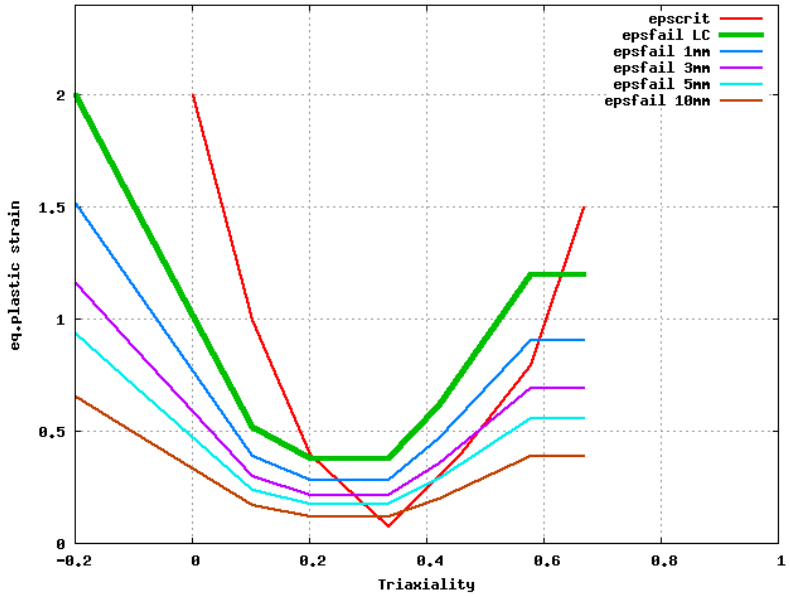
Shown is the uniaxial tensile test, similar validation was done for other experiments

Back to GISSMO : the Shearfactor

SHRF=1



SHRF=0



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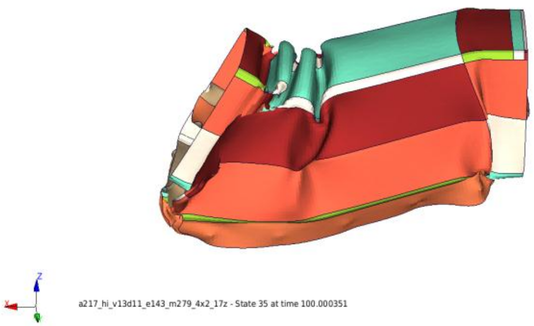
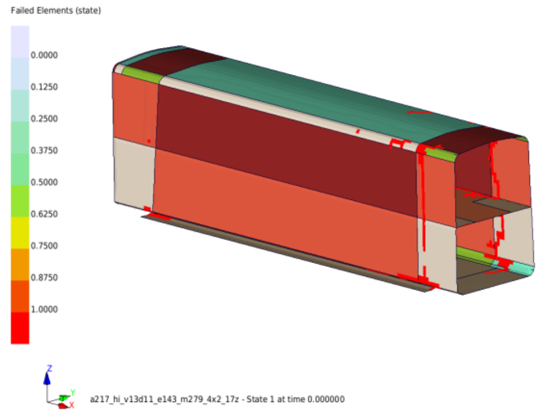
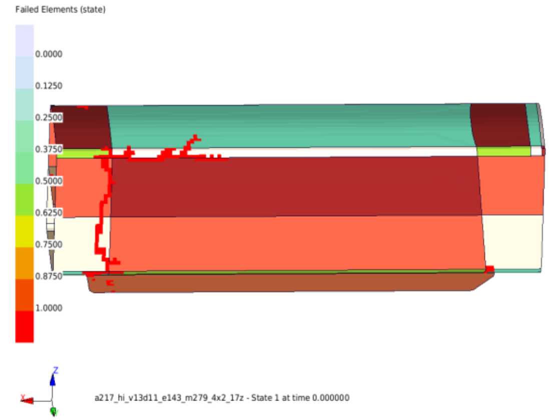
AA6014 T7 component in full car simulation

SHRF=1







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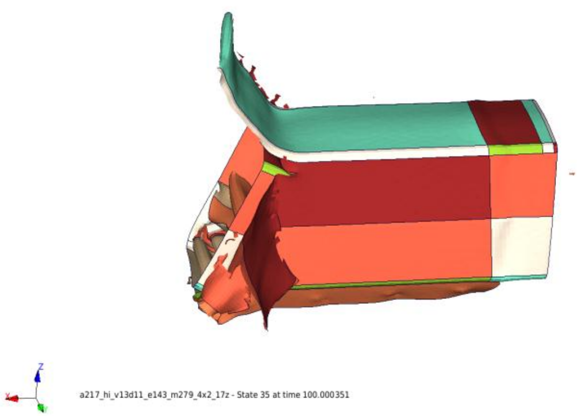

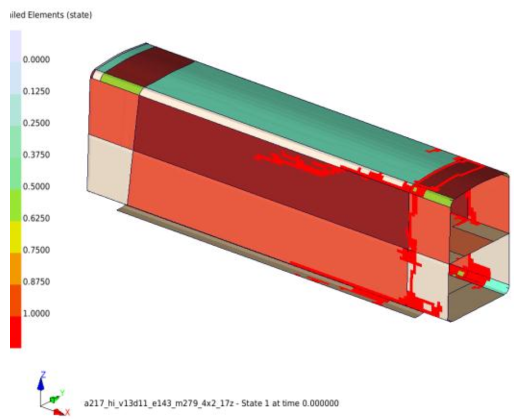

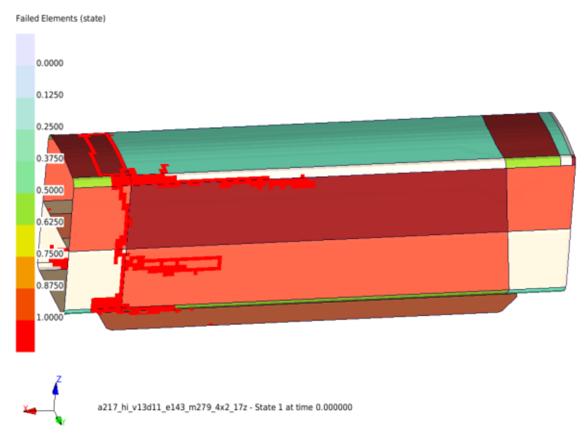

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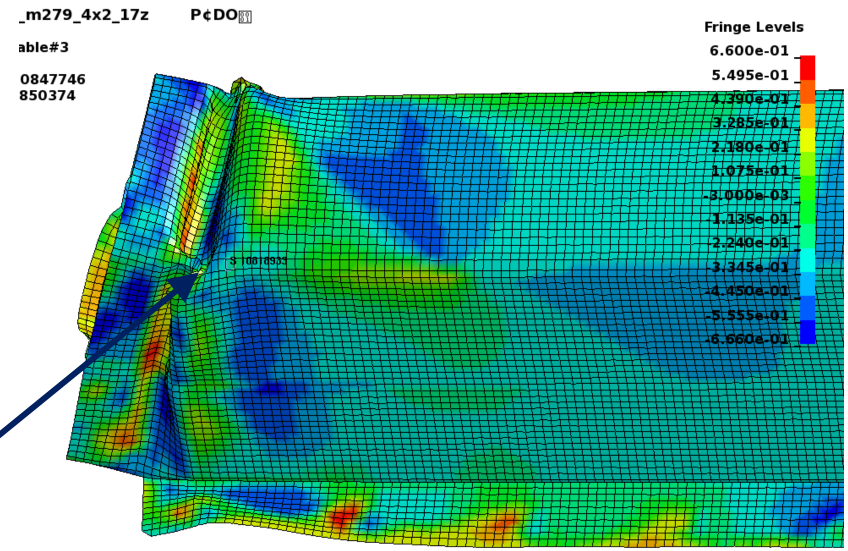
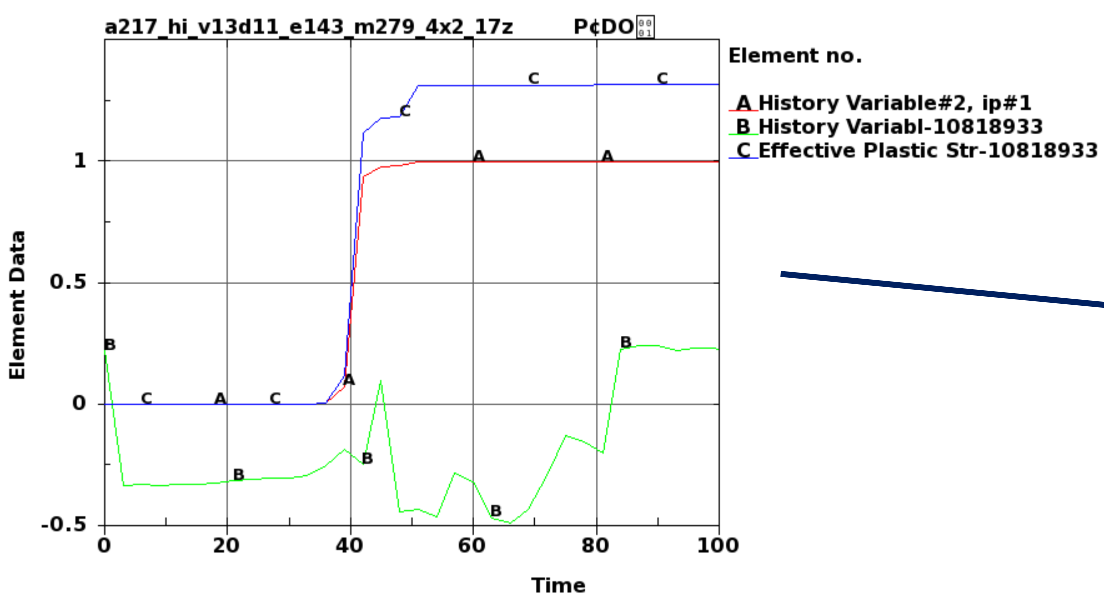
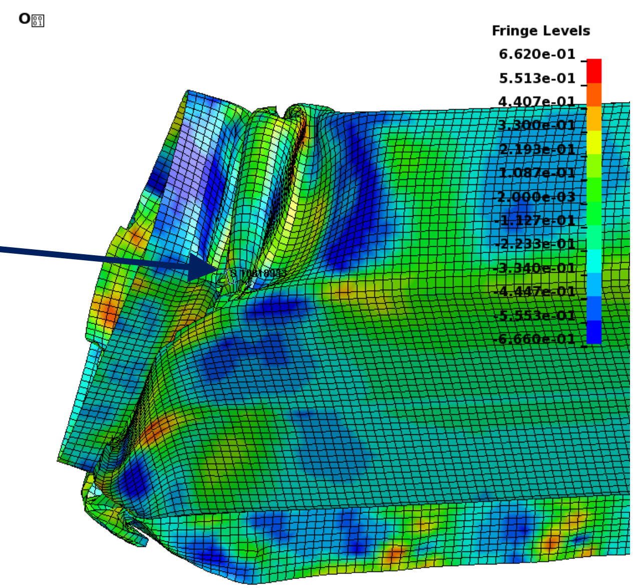
Shear failure







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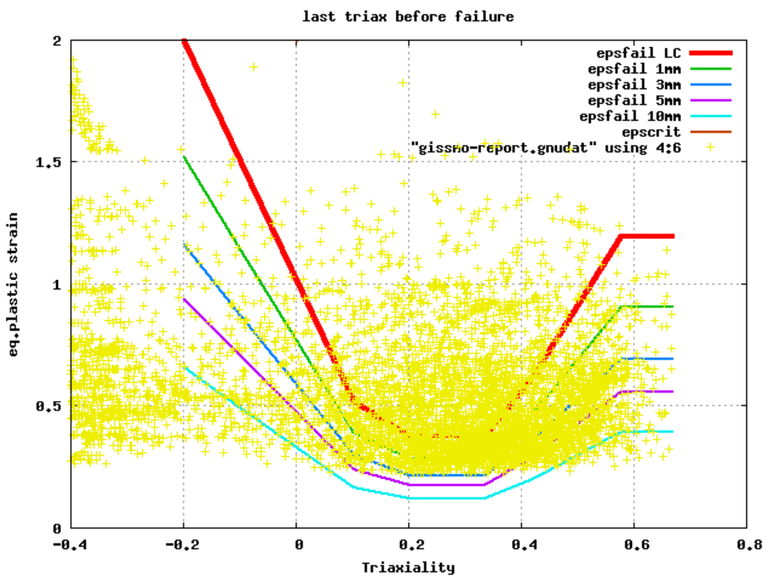
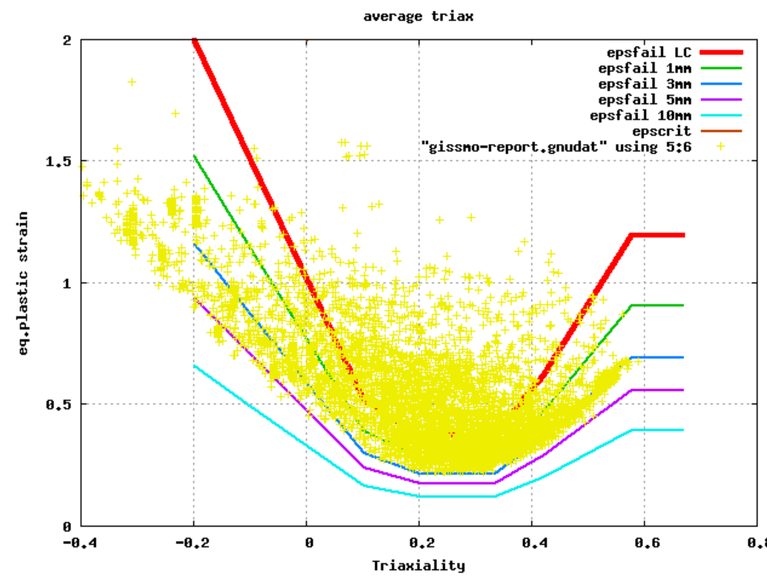
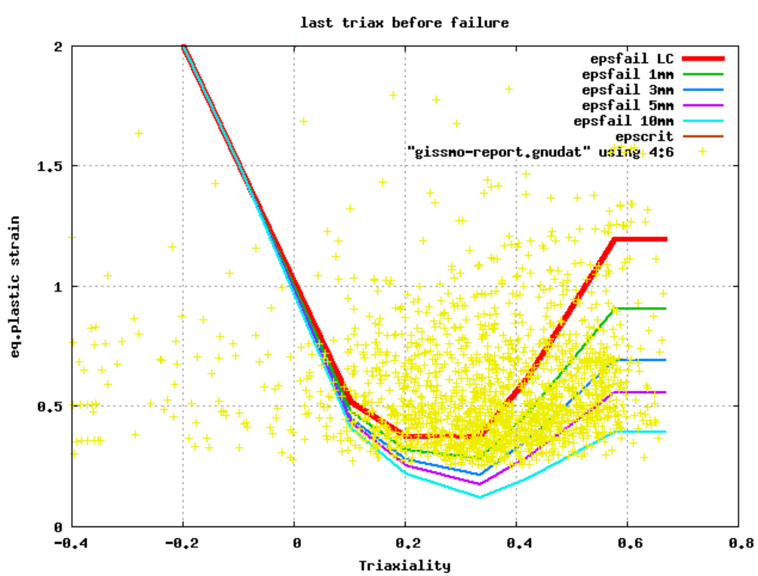
Last triax before failure | average triax

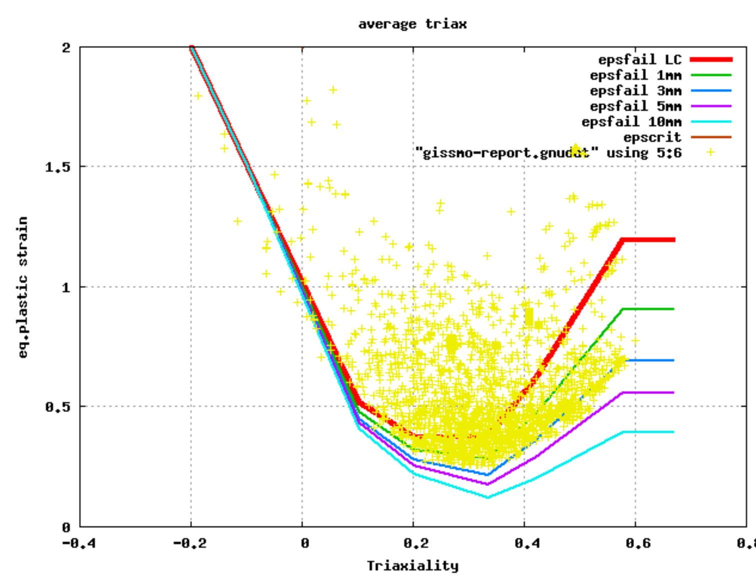
SHRF=0
BIAXF=0





SHRF=1
BIAXF=0

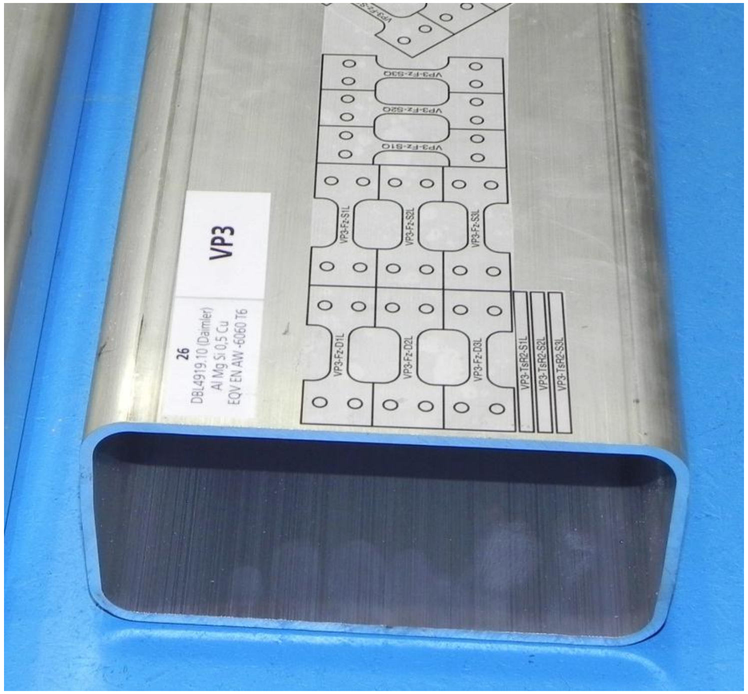




Strong anisotropic flow and damage

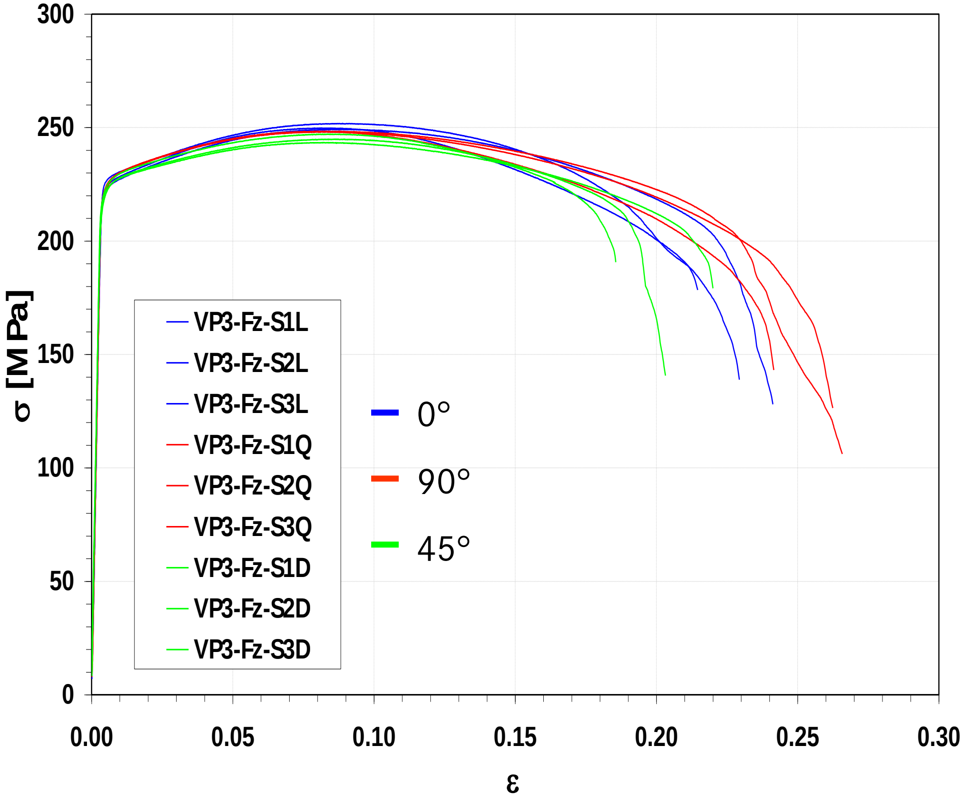
Material Data Set

- An data set was provided for material DBL4919.10
- This data set included global tensile test measurements for three different angles
  - 0°, 45° and 90°

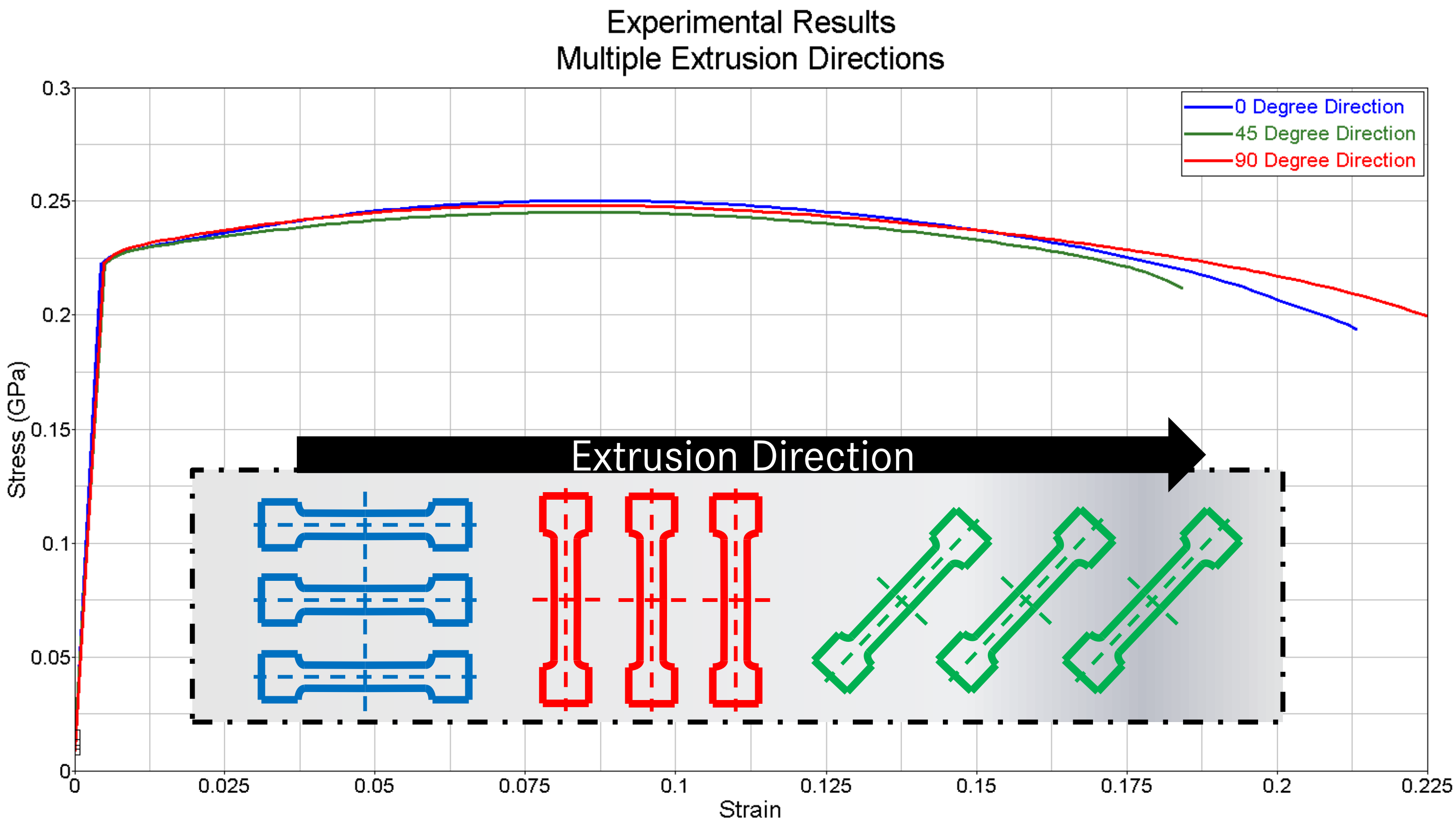


Material Anisotropy

- At first glance, the selected material does not look anisotropic based on the yield stress
- Failure strain varies, however it can be attributed to measurement scatter
- R00 was measured using the Aramis system to be 0.49 indicating strong anisotropic flow



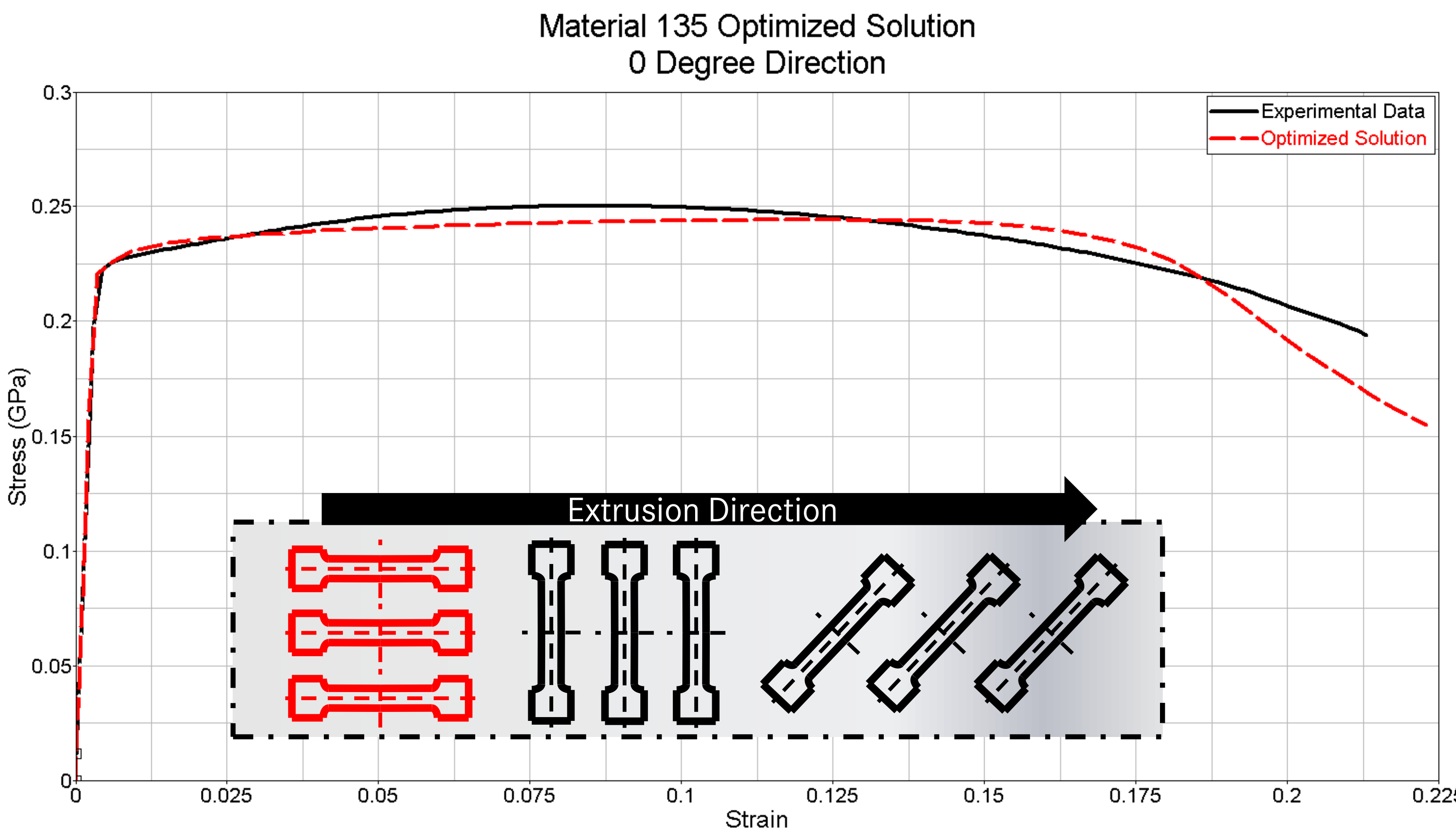
Yield curves



Optimization With Material 135

- An optimization was set up for the following variables:
  - QR1, CR1, QR2, CR2, R45 and R90
  - Other variables were measured
- Important to note that the model does not have a tabular hardening curve, rather it uses parameters (QR1, CR1, QR2, CR2)

Material 135 Optimization Results



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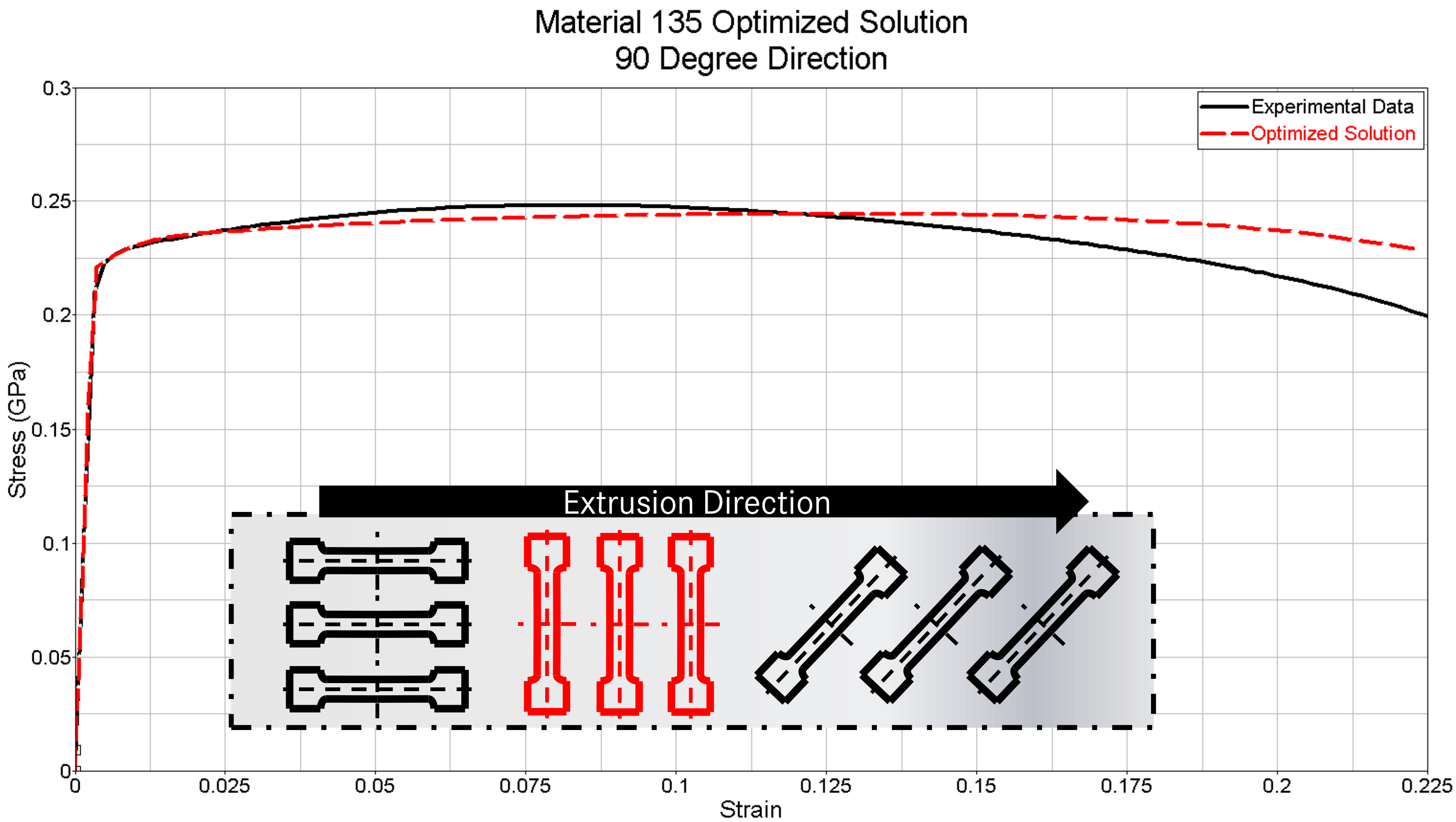
Material 135 Optimization Results



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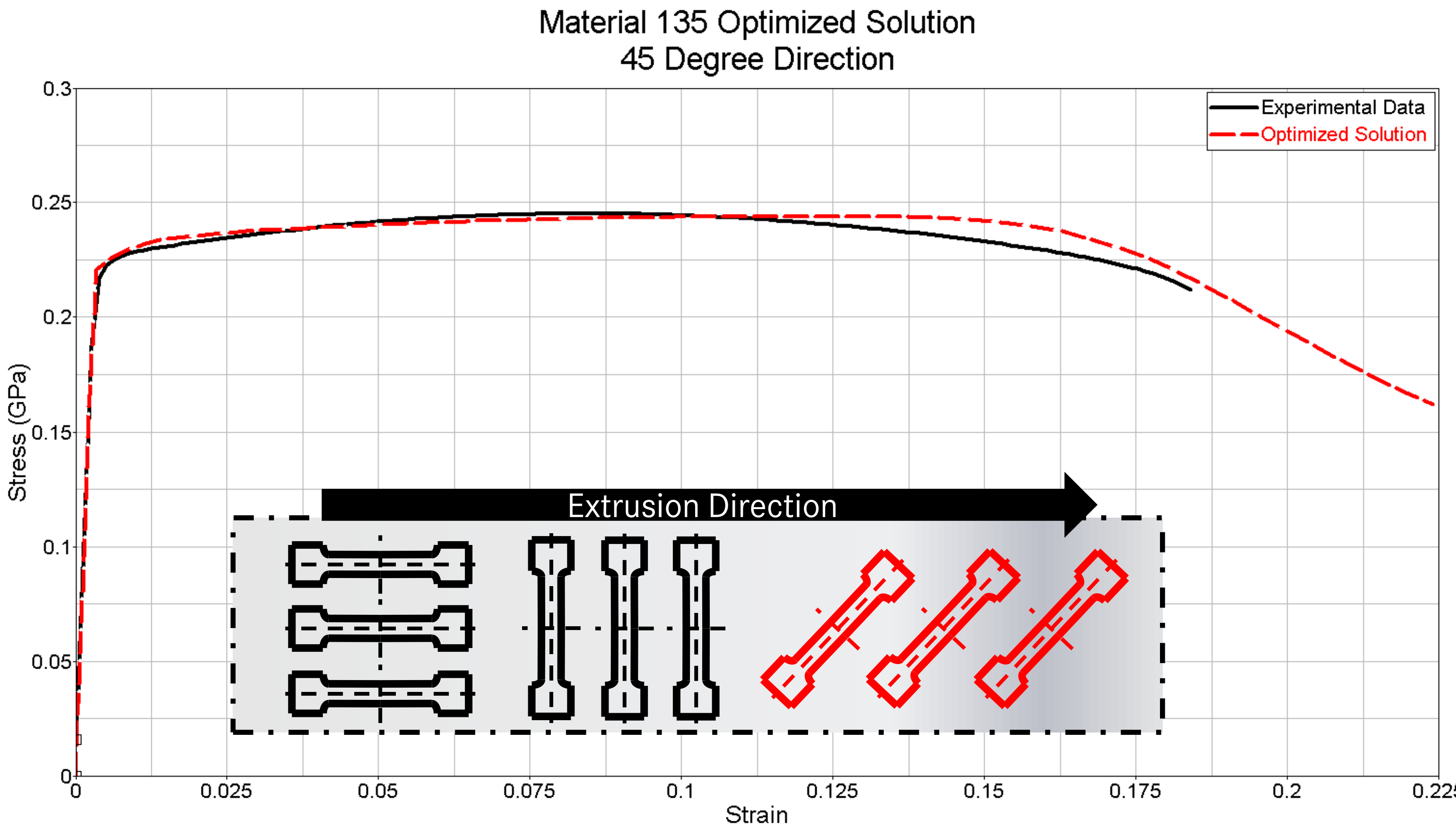
Material 135 Optimization Results



Material 135 Conclusions

- Reference material shows R values as:
  - R00 = 0.48, R45 = 0.29, R90 = 1.76
    - "Bumper Beam Longitudinal System Subjected to Offset Impact Loading" , Kokkula (PhD Thesis)
    - AA-6060 T1 Aluminum
- Optimized R values for AW-6060 T66 are:
  - R00 = 0.49, R45 = 0.323, R90 = 1.59

Material 135 Conclusions

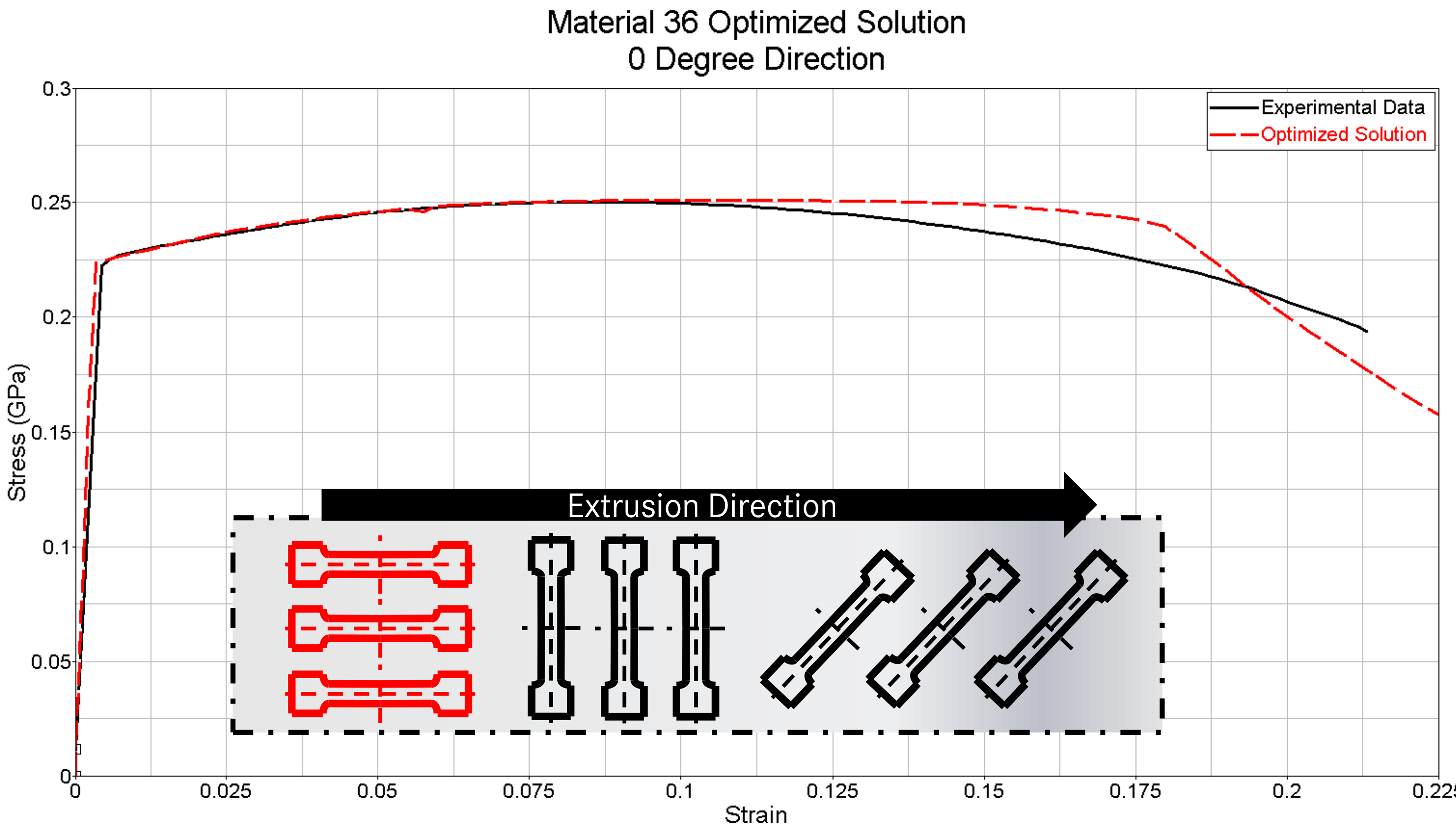
- Material 135 offers more flexibility with the anisotropic behavior of the material
- However, the yield curve inputs do not offer enough degrees of freedom to generate an accurate enough curve
- The next phase should be to test similar anisotropic material card with tabular load curve data for the hardening curves in each direction

Material 36 : Optimization Parameters

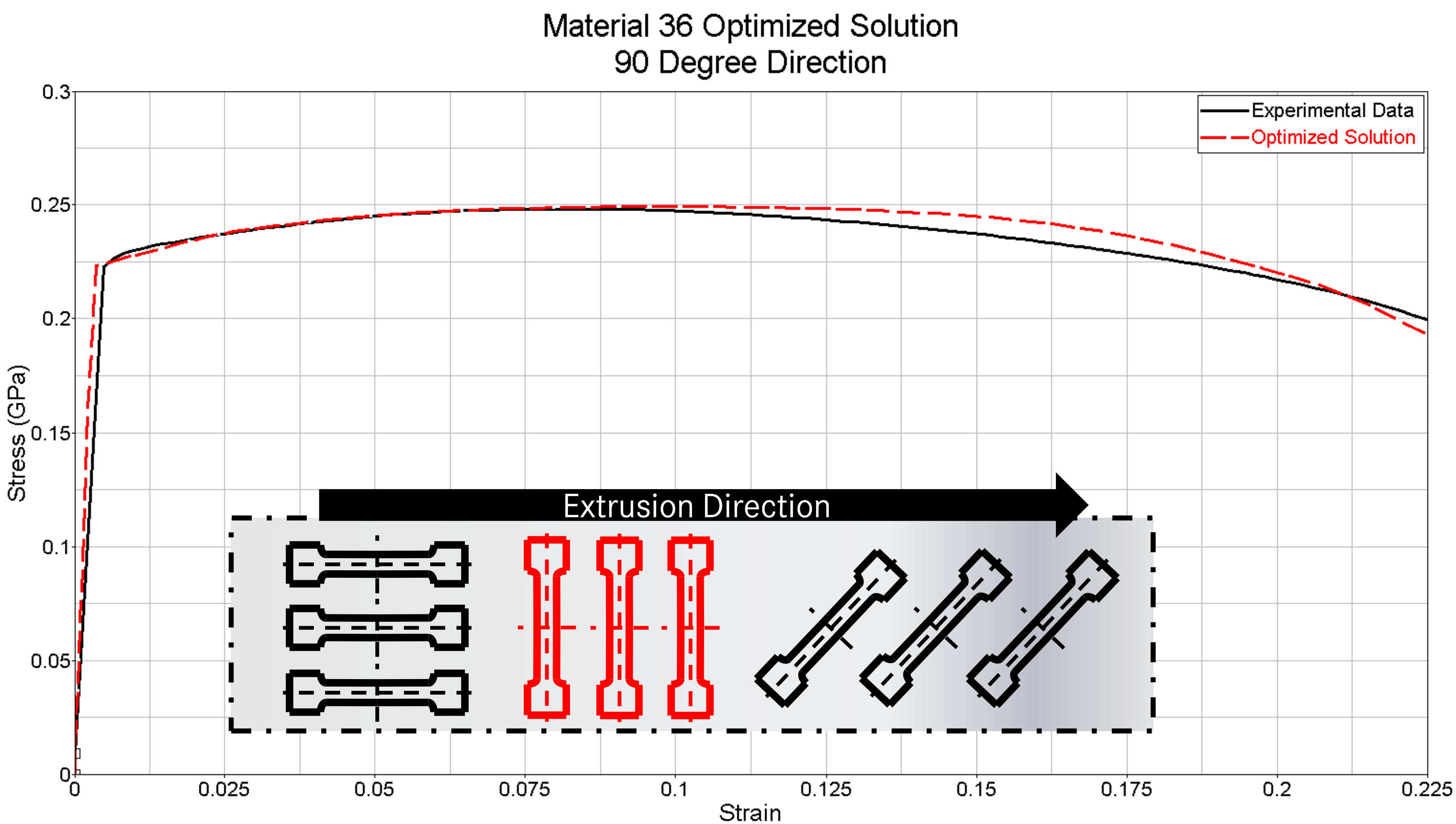
- 8 total input variables
  - Hocket-Sherby “c” variable
    - One for each extrusion direction (x3)
  - Hocket-Sherby “n” variable
    - One for each extrusion direction (x3)
  - R45
  - R90
    - R00 was measured using ARAMIS
- DYNAmat was used to generate input curves

PDB

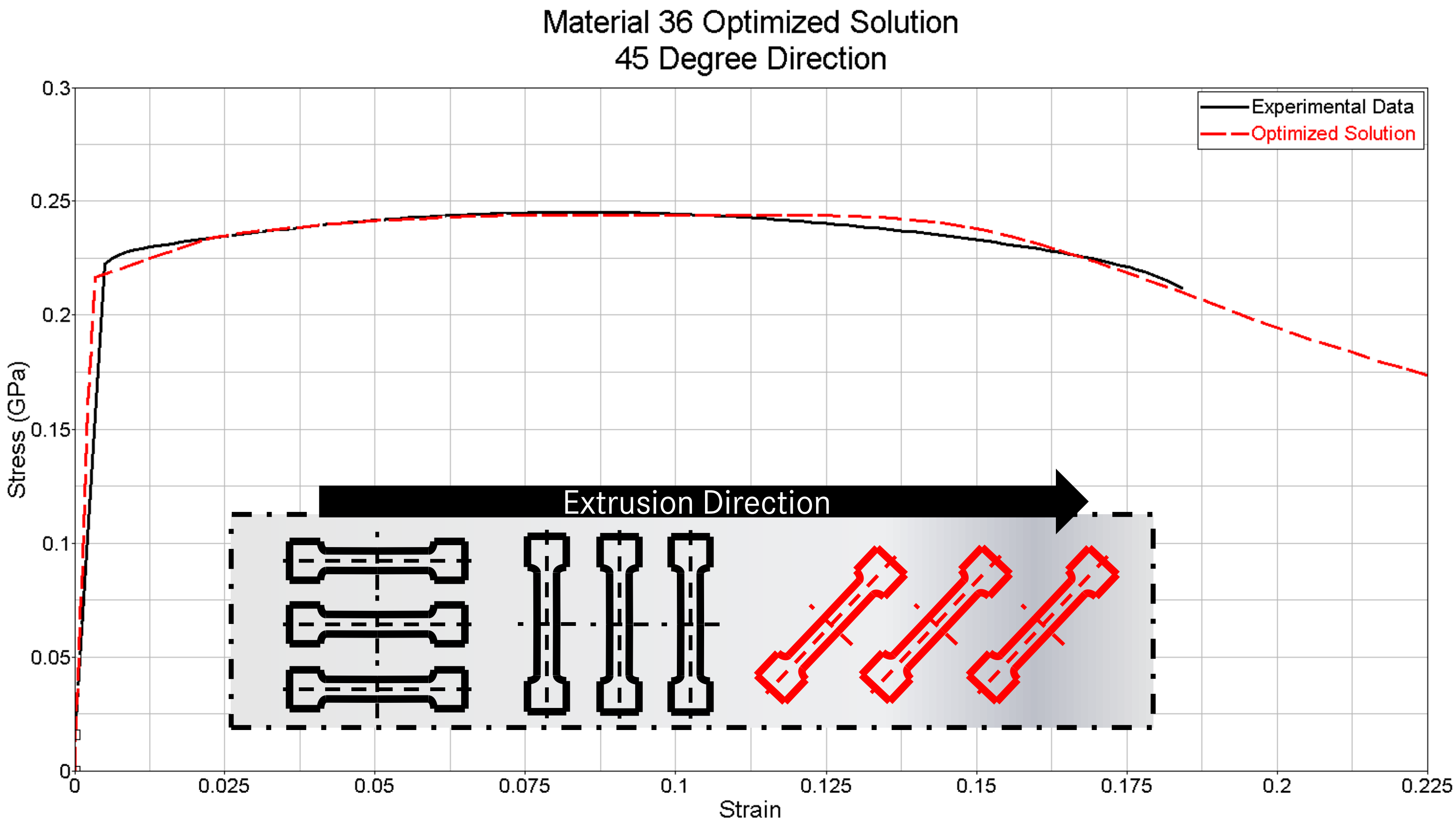
Material 36 Optimization Results



Material 36 Optimization Results



Material 36 Optimization Results



Material 36 Conclusions

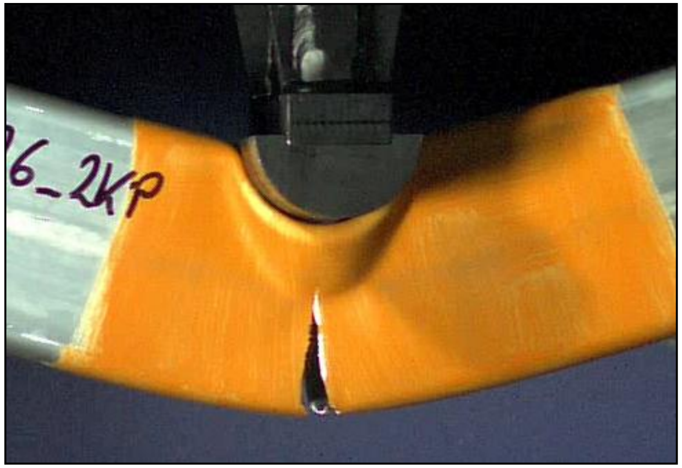
- Reference material shows R values as:
  - R00 = 0.48, R45 = 0.29, R90 = 1.76
    - “Bumper Beam Longitudinal System Subjected to Offset Impact Loading” Kokkula (PhD Thesis)
    - AA-6060 T1 Aluminum
- Optimized R values for AW-6060 T66 are:
  - R00 = 0.49, R45 = 0.27, R90 = 1.69

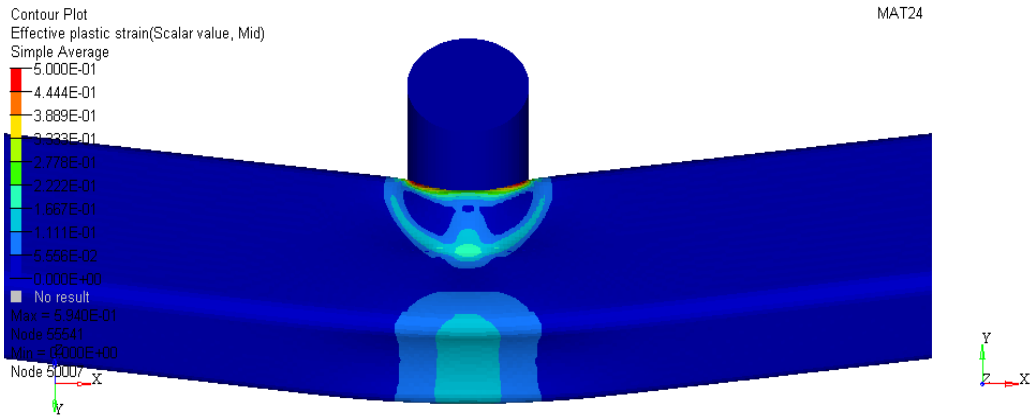
Crashworthiness Application

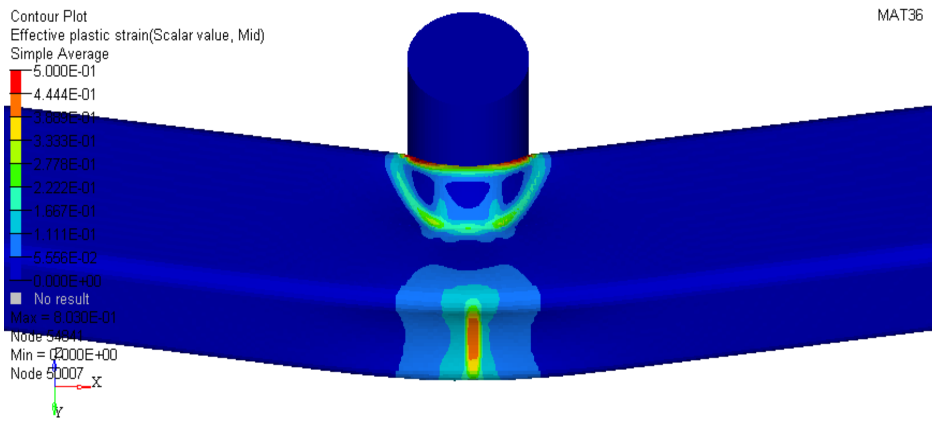
- This model was tested to improve the response/failure prediction of an extruded tube profile
- Original model was Material 24 in LSDYNA
- Initial simulations provide excellent force vs. deflection results however the simulation lacks the necessary plastic strain to create element failure

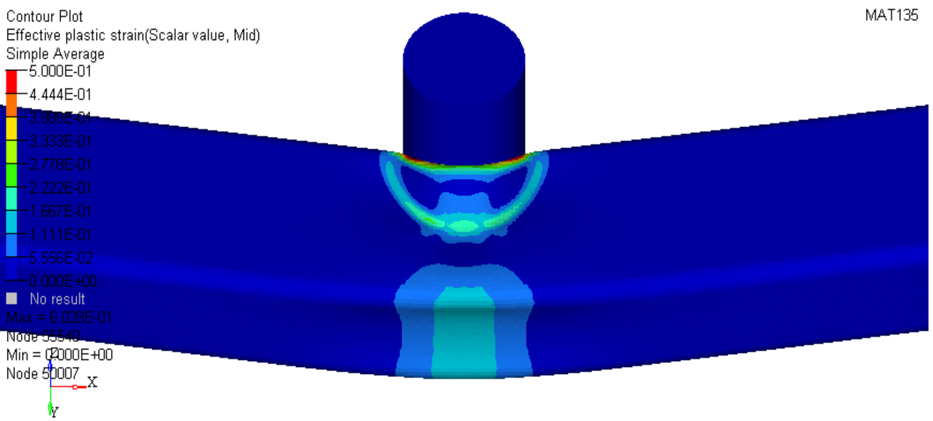
Profile Bending Simulation

Three point bending test









Summary and conclusions

- A damage and failure model must be selected in function of the application
- Damage is hard to prost-process : there is no ‚early warning' system for failure
- Regularisation is essential as for element sizes relevant to a crash model no convergence can be expected in terms of stress and strain values
- Regularisation should only be applied when needed : too much of a good thing can be bad
- Damage and failure models can only have a predictive power if the state of stress and plastic deformation are accurately simulated by the material law