A Comparison of recent Damage and Failure Models for Steel Materials in Crashworthiness Application in LS-DYNA

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Technological challenges in the automotive industry

- Safety requirements
- Weight
- New materials
- Composites
- High strength steel
- Light alloys
- Polymers
- New power train technology
- Cost effectiveness
- Design to the point

New materials

- Weight

11th LS-DYNA Users Conference June 2010

Dyna More
Technological challenges in the automotive industry

- Safety requirements
- Damage
- Anisotropy
- Failure
- Plasticity
- Weight
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- High strength steel
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- Fracture growth
- Debonding
- New power train technology
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- Deformation
- Energy
- Stress
- Strain
- Failure
- Elasticity
- Anisotropy
- Plastics
- Materials
- Safety requirements
- Cost effectiveness
- New power train technology
- Design to the point
Motivation

Lightweight steel/aluminium design!
Can we predict failure modes (brittle, ductile, time delayed)?

![Diagram showing stress-strain curves for different materials: 22MnB5, CP800, TWIP, TRIP800, ZE340, Aural.](image)
Motivation
Material behavior dependent on local history of loading

Micro-alloyed steel

Hot-formed steel
Material models along the process chain

**Forming Simulation**
- Correct description of yield locus
- Anisotropic yield locus:
  - Typical models: Barlat89, Barlat2000, Hill48, Yoshida, …

**Crash Simulation**
- Energy absorption
- Prediction of structural folding patterns
- Strain rate dependent models (including damage)
  - Typical models: von Mises, Gurson, Gurson-JC, …
Von Mises with damage
Von Mises plasticity with damage in LS-DYNA (MAT_81/82)

Enhancement of *MAT_PI ECEWISE_LINEAR_PLASTICITY(#024) with damage. Instead of abrupt failure (#024) continuous softening by damage formulation (#081/082)

- Elasto - Visco - Plasticity with isotropic Hardening and Damage:  
  No regularisation & damage/failure independent of state of stress!!

\[
D = \frac{A_d}{A_0} \quad \text{with} \quad 0.0 \leq D \leq 1.0 \\
D = \text{scalar (isotropic failure)} \\
D = D(\varepsilon^p) = \frac{\varepsilon^p - EPPF}{EPPFR - EPPF} \\
\sigma = (1 - D)C^{ep} : \varepsilon
\]

**MAT_024**: only abrupt failure  
**MAT_081**: damage, linear or nonlinear softening

![Graphs showing stress-strain behavior for different material models](image-url)
The Gurson model
The Gurson-model in LS-DYNA

- The yield function is given as
  \[
  \Phi(\sigma, \sigma_M, f) = \frac{\sigma_e^2}{\sigma_M^2} + 2q_1f^* \cosh\left(\frac{q_2 \text{tr}\sigma}{2\sigma_M}\right) - 1 - (q_1 f^*)^2 = 0
  \]

- The effective void volume fraction is defined according to
  \[
  f^*(f) = \begin{cases} 
  f & f \leq f_c \\
  f_c + \frac{1}{q_1 - f_c} \left( f - f_c \right) & f > f_c 
  \end{cases}
  \]

- For the matrix material associative von Mises plasticity is assumed for the undamaged state.
- Yield is NOT isochoric though!
- \( q_1 \) and \( q_2 \) are free parameters of the model to fit the yield surface to experimental data.
- \( f_c \) is the critical void volume fraction above which the voids start to combine and grow.
- Failure is being initiated at \( f^*(f_F) = \frac{1}{q_1} \)

\( \sigma_e \) = equivalent von Mises stress
\( \sigma_M \) = yield stress (matrix)
\( \sigma \) = stress tensor
\( f_c \) = critical void volume fraction
The Gurson-model in LS-DYNA

The growth of the void volume is $\dot{f} = \dot{f}_N + \dot{f}_G$ and can be considered as damage.

**Nucleation of new voids intensity:**

$$\dot{f}_N = A \varepsilon_{pl}^M$$

where

$$A = \frac{f_N}{s_N \sqrt{2\pi}} \exp \left( -\frac{1}{2} \left( \frac{\varepsilon_{pl}^M - \varepsilon_N}{s_N} \right)^2 \right)$$

- $\varepsilon_N$ = mean nucleation strain
- $\varepsilon_{pl}^M$ = eff. pl. strain (matrix)
- $s_N$ = std. deviation

**Growth of existing voids:**

$$\dot{f}_G = (1 - f) \varepsilon_{kk}^{pl}$$

where

$$f = \frac{V_{voids}}{V_{voids} + V_{matix}}$$

- Typical Gurson stress-strain curve
- Damaged Gurson yield surface (needs in hydrostatic loading)
Gurson enhanced by JC-failure model

- Void growth in the standard Gurson model is triggered by **volumetric straining** (see also VGTYP for differences between tension and compression for nucleation of new voids).

- Hence for **pure shear** loading softening and subsequent failure is not taking place. The Johnson-Cook enhancement adds a failure criterion that is invoked between two defined triaxiality values and triggers **sudden** failure via element erosion.

- The definition of triaxiality play a major role: \( \lambda_{\text{tri}} = \frac{\sigma_{ii}}{3\sigma_{vM}} \)

- Definition of failure strain \( \varepsilon_f = \left[ D_1 + D_2 \exp(D_3 \lambda_{\text{tri}}) \right] (1 + D_4 \ln \dot{\varepsilon}) \Lambda \)

  where \( L_1 < \lambda_{\text{tri}} < L_2 \) with \( L_1 \) and \( L_2 \) being user defined lower and upper triaxiality bounds and \( D_1 - D_4 \) are user defined Johnson-Cook failure parameters.

  \( \Lambda \) is the user defined curve LCDAM that defines a scalar value vs. element length and hence acts a regularisation means.

- **Failure** (i.e. element erosion) is initiated iff:

\[
D_i = \sum \frac{\Delta \varepsilon_p}{\varepsilon_f} \begin{cases} < 1 & \text{no failure} \\ \geq 1 & \text{failure (element erosion)} \end{cases}
\]
The Gurson_JC-model
Interaction between submodels by definition of L1 and L2

Remember: L1 and L2 are triaxiality values. Triaxility is defined as

$$\lambda_{\text{tri}} = \frac{\sigma_{ii}}{3\sigma_{vM}}$$

Hence positive values define tension, negative define compression.

The following holds for the JC-corridor:

- $$\lambda_{\text{tri}} < L2$$ Only Gurson is active
- $$L2 \leq \lambda_{\text{tri}} \leq L1$$ Gurson and JC-criteria is active
- $$L1 < \lambda_{\text{tri}}$$ Only Gurson is active
Produceability to Serviceability
Closing the process chain

Forming simulation

- Hill based models
- Anisotropy of yield surface
- Kinematic/Isotropic hardening
- Failure by FLD (post-processing)
- No computation of damage

Crash simulation

- v. Mises or Gurson model
- Strain rate dependency
- Isotropic hardening
- Damage evolution
- Failure models (damage variable necessary!!)
Different ways to realize a consistent modeling

One Material Model for Forming and Crash Simulation

- Requirements for Forming Simulations: Anisotropy, Exact Description of Yield Locus, Kinematic Hardening, etc.
- Requirements for Crash Simulation: Dynamic Material Behavior, Failure Prediction, Energy Absorption, Robust Formulation
- Leads to very complex model

Modular Concept for the Description of Plasticity and Failure

- Plasticity and Failure Model are treated separately
- Existing Material Models are kept unaltered
- Consistent modeling through the use of one damage model for forming and crash simulation

*MAT_ADD....(damage)
Produceability to Serviceability

- Anisotropy
- Yield locus

Forming simulation

Barlat

\[ \sigma, \varepsilon_{pl} \]

Gurson

\[ f \]

Mapping

\[ \varepsilon_{pl}, t \]

Crash simulation

Gurson

\[ 0^* \varepsilon_{pl,0}, t_0, f_0 \]

Incompatible Models: Isochoric plastic behavior

Schmeing, Haufe & Feucht [2007]
Neukamm, Feucht & Haufe [2007]
Produceability to Serviceability: Modular Concept

Modular Concept:
- Proven material models for both disciplines are retained
- Use of one continuous damage model for both

Forming simulation
Material model
\( \sigma, \varepsilon_{pl} \)
Damage model
\( D \)

Mapping
\( \varepsilon_{pl}, t \)

Crash simulation
Material model
\( \sigma, \varepsilon_{pl} \)
Damage model
\( D \)
Produceability to Serviceability: Modular Concept
Current status in 971R5

Forming simulation
Barlat
GISSMO

Mapping
Fortran-Program

Crash simulation
Mises
GISSMO

Ebelsheiser, Feucht & Neukamm [2008]
Neukamm, Feucht, DuBois & Haufe [2008-2010]
GISSMO – a short description
Effective stress concept (similar to MAT_81/224 etc.)

Overall Section Area containing micro-defects

\[ S \]

Reduced (“effective“) Section Area

\[ \hat{S} < S \]

Measure of Damage

\[ D = \frac{S - \hat{S}}{S} \]

Reduction of effective cross-section leads to reduction of tangential stiffness

\[ \sigma^* = \sigma (1 - D) \]

\[ \text{ Phenomenological description} \]
GISSMO - a short description
Ductile damage and failure

Damage Evolution

\[ \dot{D}_f = \frac{n}{\dot{\varepsilon}_f} D_f^{(1-\frac{1}{n})} \dot{\varepsilon}_p \]

Damage overestimated for linear damage accumulation

Failure Curve

Neukamm, Feucht, DuBois & Haufe [2008-2010]
GISSMO – a short description
Engineering approach for instability failure

Evolution of Instability

\[ \Delta F = \frac{n}{\varepsilon_{v,\text{loc}}} F \left( 1 - \frac{1}{n} \right) \Delta \varepsilon_v \]

Material Instability

Neukamm, Feucht, DuBois & Haufe [2008-2010]
REMARK: Failure criterion for plane stress and 3D solids

- For shells (2D with the assumption of plane stress) triaxiality and Lode angle depend on each other.
  - fracture strain is a function of the triaxiality

- For Solids (3D) both the Lode angle and triaxiality are independent
  - fracture strain is a function of triaxiality and Lode angle
GISSMO – a short description
Inherent mesh-size dependency of results in the post-critical region
Simulations of tensile test specimen with different mesh sizes

![Graph showing engineering stress vs. engineering strain for different mesh sizes. The graph includes lines for experiment, 0.5mm, 1mm, and 2.5mm element sizes. The graph highlights the influence of damage in the postcritical region and the regularization of mesh-size dependency.](image-url)
GISSMO – a short description
Generalized Incremental Stress State dependent damage MOdel

DMGTYP: Flag for coupling (Lemaitre)

\[ \sigma^* = \sigma \left( 1 - D \right) \]

DCRIT, FAEXP: Post-critical behavior

\[ \sigma^* = \sigma \left( 1 - \frac{D - D_{\text{CRIT}}}{1 - D_{\text{CRIT}}} \right)^{\text{FAEXP}} \]
GISSMO
Identification of damage parameters: Range of experiments and simulations

To be considered:
8 Specimen geometries
5 Discretisations
GISSMO
Equivalent plastic strain vs. triaxiality

$\varepsilon_f$ vs. triaxiality

Element size 1mm
GISSMO vs. Gurson vs. 24/81
Comparison of experiments and simulations
Gurson vs. GISSMO – “regularized”
Regularization of element size dependency

**Gurson**
- Resultant Failure Strain constant
- Failure energy depending on el. size
- Identification of damage parameters is difficult

**GISSMO**
- Failure Strain constant
- Fracture energy constant
- Identification of Damage Parameters is more straight-forward
Example: tension rod

GISSMO input

damage

instability

Element no.

A. X-stress, i/max

B. Effective Stress (σ-m), ip-294

C. History Variable#6, ip-294

D. History Variable#6, ip-294

E. History Variable#6, ip-294
Example: Arcan shear test

- **Damage**
  - Time vs. History Variable of surf
  - Element no.: 530, 538, 537

- **Triaxiality**
  - Time vs. History Variable of surf
  - Element no.: 530, 538, 537

- **Instability**
  - Equivalent Plastic Strain vs. Triaxiality

**Graphs and Diagrams:**
- Arcan-Scherprobe plots showing time vs. damage and triaxiality vs. damage and instability.

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GISSMO
Deep-draw simulation of cross-die using GISSMO

- Constant failure criterion
- Linear damage accumulation
- Failure not predicted correctly

- GISSMO-Criterion
- Linear accumulation of damage
- Possibly overestimated damage

- GISSMO-Criterion
- Nonlinear damage accumulation
- Rupture predicted correctly
Process chain with GISSMO

Forming simulation:
*MAT_36 (Barlat '89)
*MAT_ADD_EROSION (GISSMO)

Crash Simulation:
*MAT_24 (Mises)
*MAT_ADD_EROSION (GISSMO)

Mapping

Plast. strains
Thickness distribution
Damage
Summary

- Features of GISSMO:
  - The use of existing material models and respective parameters
  - The constitutive model and damage formulation are treated separately
  - Allows for the calculation of pre-damage for forming and crashworthiness simulations

- Characterization of materials requires a variety of tests
- Automatic method for identification of parameters is to be developed
- Offers features for a comprehensive treatment of damage in forming simulations
- Available in LS-DYNA V9.71 R5
- Verification and validation of concept are under way
Threepart failure concept
Damage and failure concept
New implementation of a three-part failure model

- By using the basic software architecture available since the implementation of GISSMO another client driven three-part failure and damage model has been implemented.
- The model will be available in *MAT_ADD_EROSION starting with LS-DYNA V971 R5.
- The concept allows (theoretically) the combination with any available constitutive model in LS-DYNA. Hence the same idea for closing the gap between forming and crash simulations apply.
- The individual criteria deliver strain rate dependent failure accumulation that is being input in tabulated from.
- Using the accumulated data in subsequent simulations (multi-stage) simulations, the well established method of using the DYNAI-files is chosen. Hence *INCLUDE_STAMPED_PART will be able to handle the new option.

Basis material model: e.g. MAT_24
Damage and failure concept

- Three individual criteria may predict failure in thin sheet metal.
- Post-critical behavior is defined by allowance of an additional displacement in each element.
- The element is deleted if a defined number of integrations points is flagged as "failed".

### Ductile failure

For the ductile initiation option a function

\[ \varepsilon_D^p = \varepsilon_D^p(\eta, \dot{\varepsilon}^p) \]

represents the plastic strain at onset of damage \((P1)\). This is a function of stress triaxiality defined as

\[ \eta = -p/q \]

with \( p \) being the pressure and \( q \) the von Mises equivalent stress. Optionally this can be defined as a table with the second dependency being on the effective plastic strain rate \( \dot{\varepsilon}^p \).

The damage initiation history variable evolves according to

\[ \omega_D = \int_0^{\varepsilon^p} \frac{d\varepsilon^p}{\varepsilon_D^p} \]

### Shear failure

For the shear initiation option a function

\[ \varepsilon_D^p = \varepsilon_D^p(\theta, \dot{\varepsilon}^p) \]

represents the plastic strain at onset of damage \((P1)\). This is a function of a shear stress function defined as

\[ \theta = \frac{(q + k_s p)}{\tau} \]

with \( p \) being the pressure, \( q \) the von Mises equivalent stress and \( \tau \) the maximum shear stress defined as a function of the principal stress values

\[ \tau = \frac{(\sigma_{\text{major}} - \sigma_{\text{minor}})}{2} \]

Introducing here is also the pressure influence parameter \( k_s \), \((P2)\). Optionally this can be defined as a table with the second dependency being on the effective plastic strain rate \( \dot{\varepsilon}^p \). The damage initiation history variable evolves according to

\[ \omega_D = \int_0^{\varepsilon^p} \frac{d\varepsilon^p}{\varepsilon_D^p} \]

### Instability criteria

For the MSFLD initiation option a function

\[ \varepsilon_D^p = \varepsilon_D^p(\alpha, \dot{\varepsilon}^p) \]

represents the plastic strain at onset of damage. This is a function of the ratio of principal plastic strain rates defined as

\[ \alpha = \frac{\dot{\varepsilon}_{\text{major}}}{\dot{\varepsilon}_{\text{minor}}} \]

The MSFLD criterion is only relevant for shells and the principal strains should be interpreted as the in-plane principal strains. The damage initiation history variable evolves according to:

\[ \omega_D = \max_{t \in T} \frac{e_D^p}{\varepsilon_D}\]
Failure mechanism in sheet metal deformation

Ductile failure criteria

\[ \varepsilon_D^D \]

Shear failure criteria

\[ \varepsilon_S^D \]

Instability failure criteria

\[ \varepsilon_I^D \]

\[ \sigma \] vs \[ \varepsilon \] for:

- Ductile failure: \[ \varepsilon_{\text{fail}} \] to \[ \varepsilon_{\text{rupt}} \]
- Shear failure: \[ \varepsilon_{\text{fail}} \] to \[ \varepsilon_{\text{rupt}} \]
- Instability: \[ \alpha = \frac{\varepsilon_2}{\varepsilon_1} \]
Thank you for your attention!