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Short Overview of Failure and Damage Models in LS-DYNA

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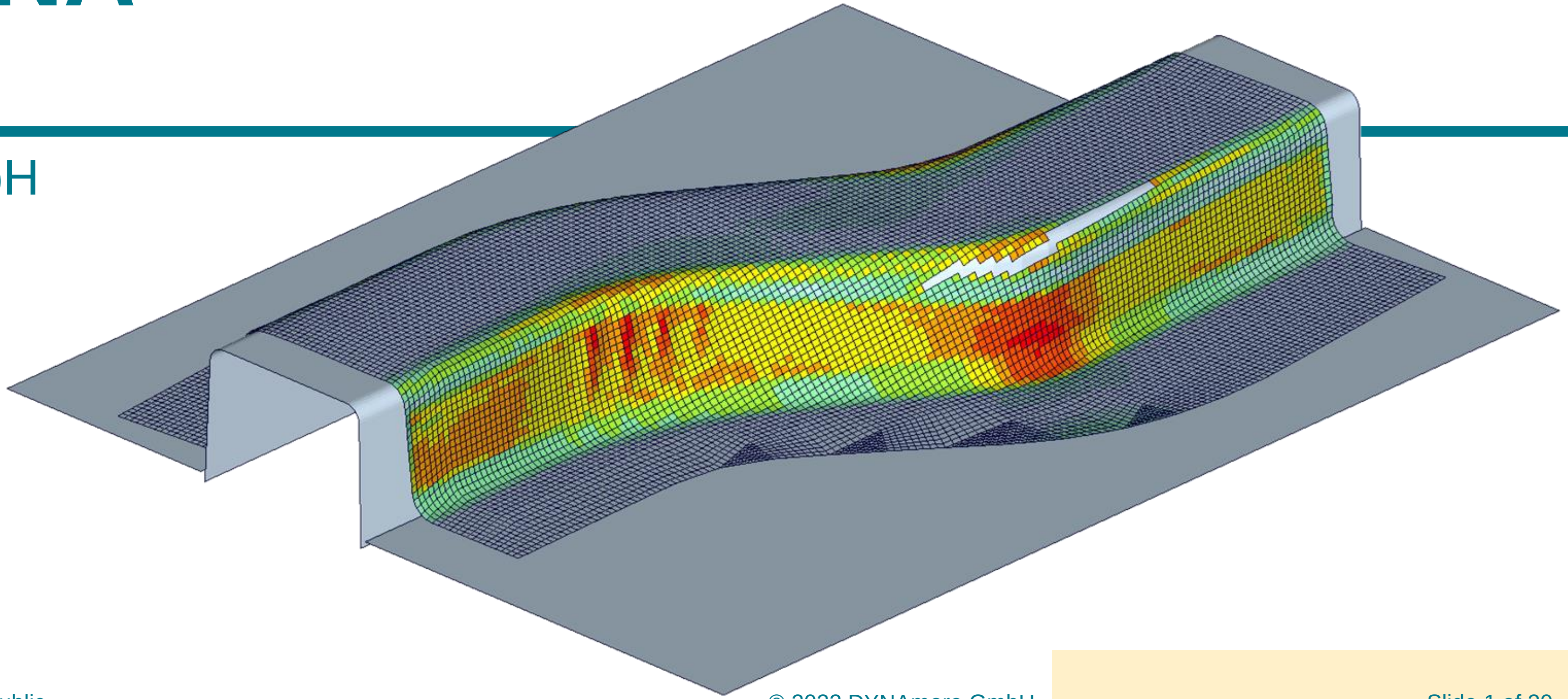
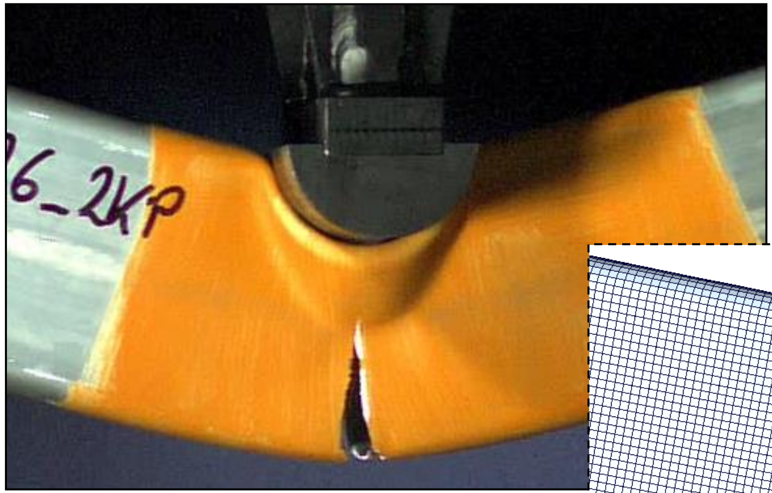
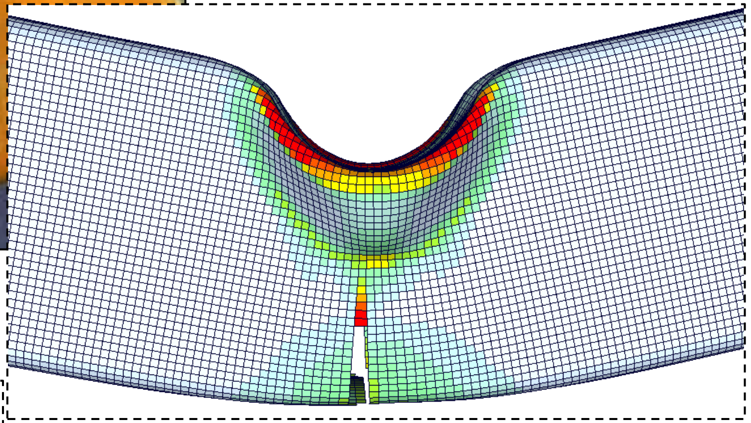
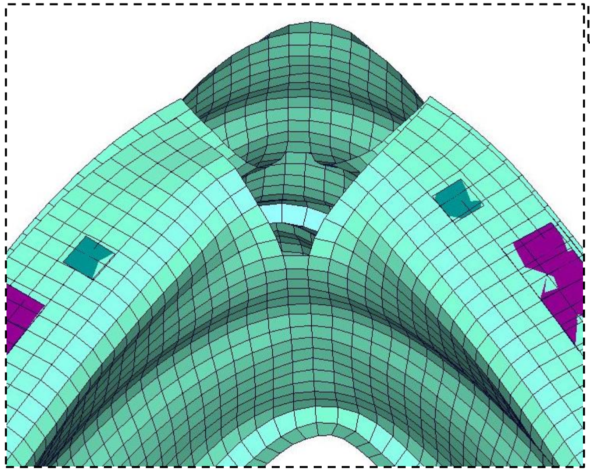
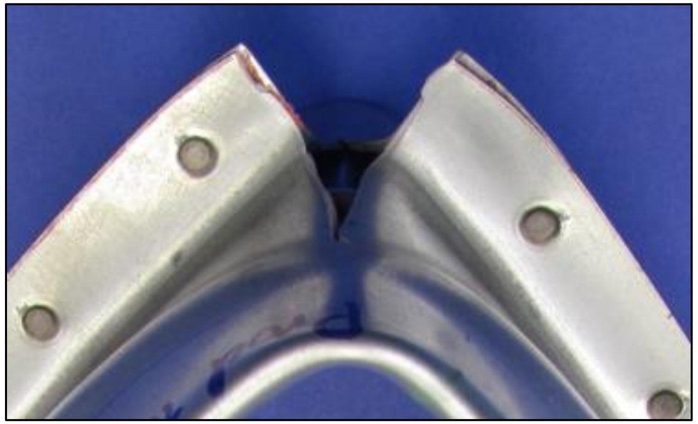


Material failure prediction

- Failure behavior depends on several aspects including plastic straining, stress state, load path, localization, strain rate, anisotropy, etc.
- Usage of failure and damage models is intended to predict failure in simulation
- Choice of failure or damage model will depend on the application and the desired accuracy

Material failure prediction

Typical modeling strategies

Failure models

- Failure variable as indicator of failure onset
- No effect on material stiffness or strength
- Some models are incremental, others aren't
- Failure models are generally simpler than damage models
- Typically less parameters to identify from experiments

Damage models

- Damage variable as indicator of failure onset
- Material stiffness/strength affected by damage
- Typically incremental
- Damage models are generally more complex than failure models
- Typically more parameters to identify from experiments

- Some models (for example, GISSMO) can be failure and damage models simultaneously
- Generally, element erosion will occur in LS-DYNA after the failure criterion is reached
- Incremental models are generally more accurate (e.g., under non-proportional loading)

Failure and damage models in LS-DYNA

Two types of implementation

Implemented within the material model

- Plasticity and failure are treated through the same keyword *MAT_...
- Examples: *MAT_JOHNSON_COOK, *MAT_123, *MAT_GURSON, *MAT_DAMAGE_1, *MAT_PLASTICITY_WITH_DAMAGE

Modular structure through *MAT_ADD_...

- Failure (or damage) is treated through an additional keyword typically beginning with *MAT_ADD_...
- Examples: *MAT_ADD_EROSION, *MAT_ADD_DAMAGE_GISSMO, *MAT_ADD_DAMAGE_DIEM, *MAT_ADD_GENERALIZED_DAMAGE
- Link between plasticity and failure (or damage) model is achieved by using the same material ID in both keywords

Failure models

Failure models

An overview of some typical failure models available in LS-DYNA

- ***MAT_PIECEWISE_LINEAR_PLASTICITY (#024)**
  Von Mises based elasto-plastic material model with isotropic hardening and strain rate effects;
  Failure criterion based on the plastic equivalent strain
- ***MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY (#123)**
  Similar to *MAT_024 with additional options
  Failure criteria based on plastic equivalent strain, thinning strain and/or major strain
- ***MAT_JOHNSON_COOK (#015)**
  ***MAT_MODIFIED_JOHNSON_COOK (#107)**
  Temperature and strain rate dependent material with a failure criterion as a function of the stress triaxiality ratio
- ***MAT_WTM_STM (#135)**
  An orthotropic elasto-plastic material model for shell elements
  The Cockcroft-Latham and Bressan-Williams fracture criteria are embedded in this model
- ***MAT_ADD_EROSION**
  Modular concept to add failure criteria to existing material models

Some of the models above can be reproduced by GISSMO or DIEM through *MAT_ADD_EROSION

*MAT_PIECEWISE_LINEAR_PLASTICITY (#24)

Failure criterion: Equivalent plastic strain at failure

Equivalent plastic strain at failure

```
*MAT_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  7.85E-06     210.0       0.3                          0.25
$        C         P      LCSS      LCSR        VP
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8
```

- Very simple criterion in *MAT_024 through the flag “FAIL”
- The equivalent plastic strain is compared to the value of FAIL
- Shell element is deleted if ALL integration points fulfill the criterion
- No stress state or strain rate dependence (failure behavior under tension or compression is identical)
- Not incremental

*MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY (#123)

Three failure criteria available

Equivalent plastic strain at failure

```
*MAT_MODIFIED_PIECEWISE_LINEAR_PLASTICITY
$      MID        RO         E        PR      SIGY      ETAN      FAIL      TDEL
         1  7.85E-06     210.0       0.3                          0.25
$        C         P      LCSS      LCSR        VP   EPSTHIN    EPSMAJ    NUMINT
                           100                   1
$     EPS1      EPS2      EPS3      EPS4      EPS5      EPS6      EPS7      EPS8

$      ES1       ES2       ES3       ES4       ES5       ES6       ES7       ES8
```

Thinning strain at failure

Major in-plane strain at failure

- Material model similar to *MAT_024 but with two additional failure criteria
- In the case of shell elements, NUMINT defines how many integration points have to fail before the element is deleted
- Not incremental

*MAT_ADD_EROSION

Several simple failure criteria available

```
*MAT_ADD_EROSION
$      MID      EXCL    MXPRES     MNEPS    EFFEPS    VOLEPS    NUMFIP       NCS
         1                                     0.5                             2
$   MNPRES     SIGP1     SIGVM     MXEPS     EPSSH     SIGTH   IMPULSE    FAILTM
                                     0.3
```

- MXPRES: Maximum pressure at failure
- MNEPS: Minimum principal strain at failure
- EFFEPS: Effective strain at failure
- VOLEPS: Volumetric strain at failure
- NCS: Number of failure criteria to be satisfied before element deletion (default=1)
- MNPRES: Minimum pressure at failure
- SIGP1: Principal stress at failure
- SIGVM: Equivalent stress at failure
- MXEPS: Maximum principal strain at failure
- EPSSH: Shear strain at failure
- FAILTM: Failure time

- *MAT_ADD_EROSION is based on a modular concept containing several simple failure criteria
- To activate it, just add the keyword using the same material ID of the base material for which the failure criterion should be used
- Not incremental

Johnson-Cook failure criterion

An **incremental** failure criterion based on triaxiality, strain rate and temperature

The fracture strain is given by

$$\varepsilon^f = (D_1 + D_2 \exp(D_3\sigma^\star))\,(1 + D_4 \ln \dot{\varepsilon})\,(1 + D_5 T^\star)$$

$$\sigma^\star = \frac{p}{\sigma_{eq}} = -\eta$$

stress triaxiality

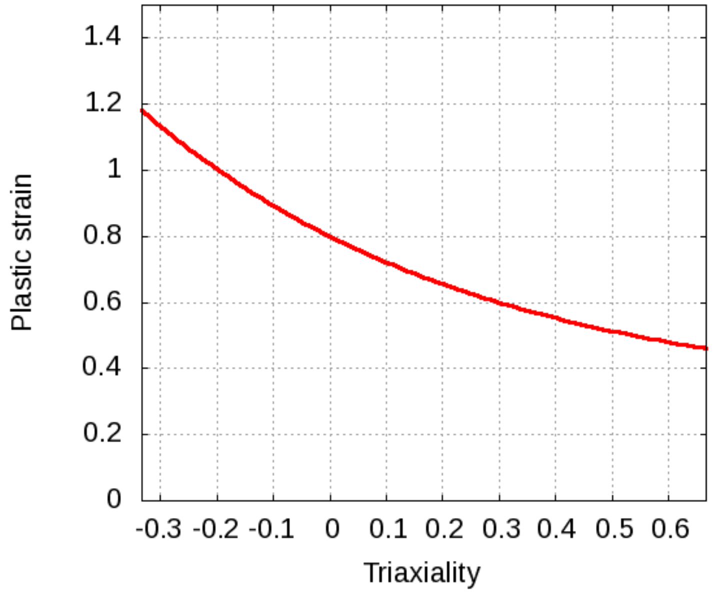
$$T^\star = \frac{T - T_{room}}{T_{melt} - T_{room}}$$

A "damage" value is accumulated:

$$D = \sum \frac{\Delta\varepsilon^p}{\varepsilon^f}$$

Fracture occurs if D=1.

Available in *MAT_015 or *MAT_107 but can be fully reproduced by GISSMO or DIEM through *MAT_ADD_EROSION



Cockcroft-Latham failure criterion

An **incremental** criterion based on the first principal stress and deformation history

Cockcroft and Latham (1968) proposed a simple failure criterion where a failure value W is accumulated based on the incremental of accumulated plastic strain and the current principal stress:

$$\int_0^{\varepsilon^f} \max\left(\sigma_1, 0\right) d\varepsilon^p = W \qquad \text{failure takes place if} \quad W \geq W_c$$

In LS-DYNA, this criterion is for instance available in *MAT_135:

Critical value Wc for the Cockcroft-Latham failure criterion

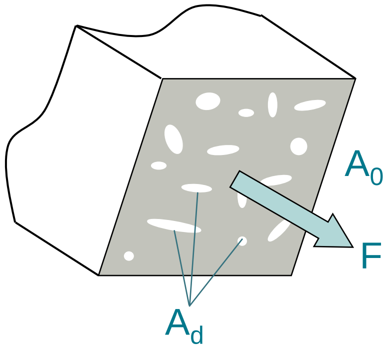
```
*MAT_WTM_STM
$      MID        RO         E        PR     NUMFI      EPSC        WC      TAUC
         1   7.85E-6     210.0       0.3                             0.6
$   SIGMA0       QR1       CR1       QR2       CR2         K        LC       FLG
      -100                                                 4                   1
$      S00       S45       S90       SBB       R00       R45       R90       RBB
     0.200     0.198     0.210     0.215      0.80      0.91      1.12      1.05
$      QX1       CX1       QX2       CX2      EDOT         M      EMIN      S100

$ ... ...
```

Damage models

Overview of damage models in LS-DYNA

Lemaitre-based models	*MAT_DAMAGE_1 (#104) *MAT_DAMAGE_2 (#105) *MAT_DAMAGE_3 (#153)
Gurson-based models	*MAT_GURSON (#120) *MAT_GURSON_JC (#120_JC) *MAT_GURSON_RCDC (#120_RCDC)
Modular damage/failure models in LS-DYNA	*MAT_ADD_EROSION, IDAM=1 (GISSMO) *MAT_ADD_EROSION, IDAM<0 (DIEM) *MAT_ADD_GENERALIZED_DAMAGE (eGISSMO)
Other damage models	*MAT_PLASTICITY_WITH_DAMAGE (#81) *MAT_PLASTICITY_WITH_DAMAGE_ORTHO (#82) *MAT_ORTHOTROPIC_SIMPLIFIED_DAMAGE (#221) *MAT_TABULATED_JOHNSON_COOK (#224)



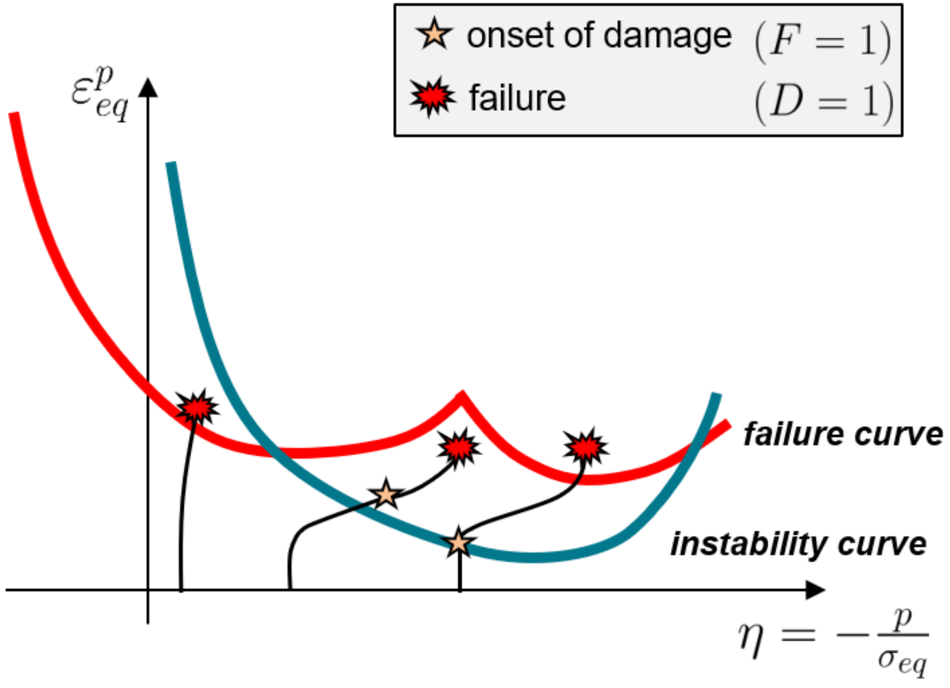
From LS-DYNA R11 on **also** available as:

→ *MAT_ADD_DAMAGE_GISSMO (for *MAT_ADD_EROSION, IDAM=1)

→ *MAT_ADD_DAMAGE_DIEM (for *MAT_ADD_EROSION, IDAM<0)

GISSMO

Generalized **I**ncremental **S**tress **S**tate dependent **MO**del



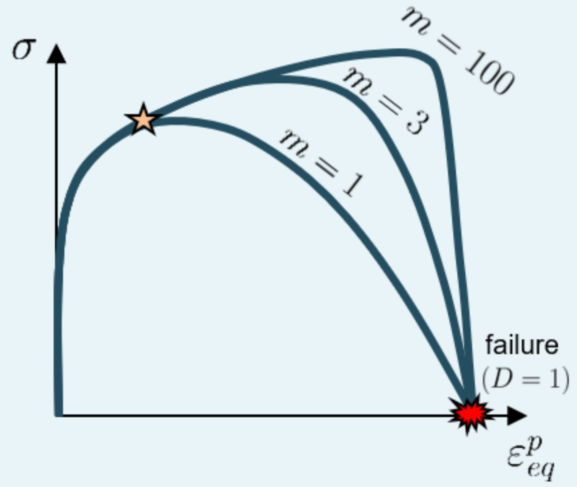
$$\dot{F} = \frac{n}{\varepsilon_{inst}(\eta)} F^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}^p_{eq}$$ ***(instability measure)***

$$\dot{D} = \frac{n}{\varepsilon_{fail}(\eta)} D^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}^p_{eq}$$ ***(damage measure)***

$F = 1$ → **Onset of damage**

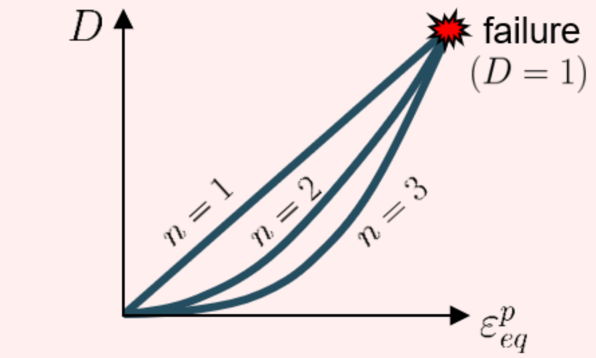
$$\boldsymbol{\sigma} = \left(1 - \tilde{D}\right) \boldsymbol{\sigma}_{eff}$$

$$\tilde{D} = \left(\frac{D - D_{crit}}{1 - D_{crit}}\right)^m$$

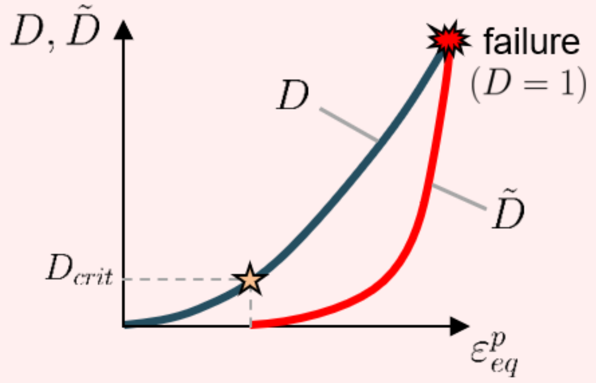


Effect of the fading exponent (m)

Damage over strain



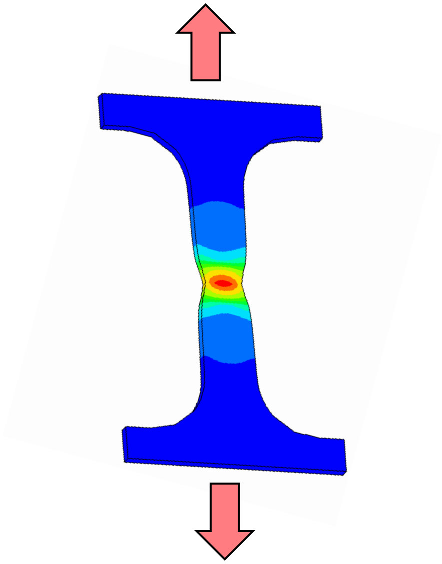
Effect of the damage exponent (n)



Accumulation of D and $\tilde{D}$

DIEM

Damage Initiation and Evolution Model

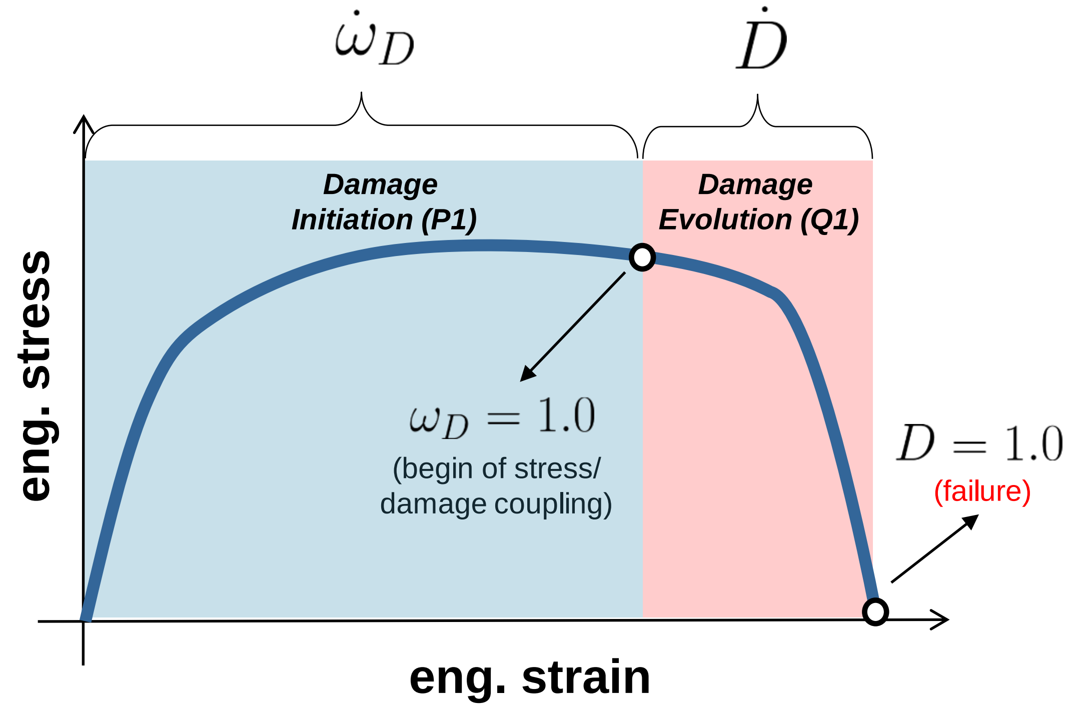


```
*MAT_ADD_EROSION
$      MID        EXCL     MXPRES      MNEPS . . .
       100
$   MNPRES      SIGP1      SIGVM      MXEPS . . .

$     IDAM
        -3
$ ----- Ductile initiation criterion
$    DITYP         P1         P2         P3
         0        100
$    DETYP      DCTYP         Q1         Q2
         0          0        0.1
$ . . .
```

Damage initiation (DI): Accumulation of an initiation variable ω_D

Damage evolution (DE): Accumulation of a damage variable D
Stress and damage are coupled (softening!)



DIEM

Damage **I**nitiation and **E**volution **M**odel

Damage **I**nitiation variable $\longrightarrow \omega_D^i$

- Each damage initiation criterion has its own stress state indicator: triaxiality, shear stress function and deviatoric stress ratio
- The different stress state indicators can, under certain limitations, be mutually converted

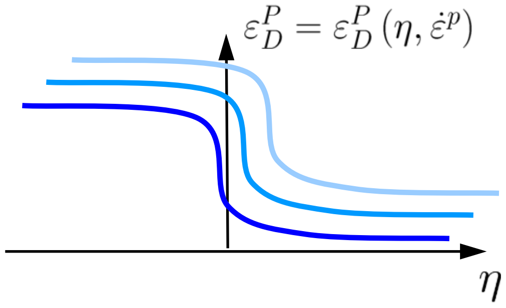
Ductile

`DITYP=0`

$$\omega_D^0 = \int_0^{\varepsilon^p} \frac{\mathrm{d}\varepsilon^p}{\varepsilon_D^p}$$

triaxiality:

$$\eta = -\frac{p}{\sigma_{eq}}$$



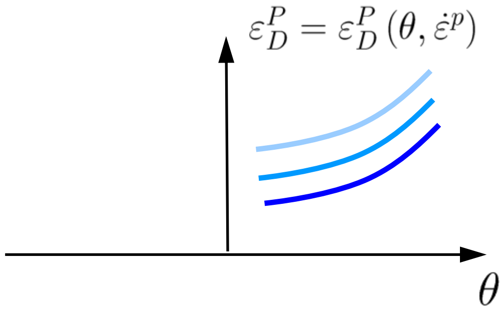
Shear

`DITYP=1`

$$\omega_D^1 = \int_0^{\varepsilon^p} \frac{\mathrm{d}\varepsilon^p}{\varepsilon_D^p}$$

shear stress function:

$$\theta = \frac{2(\sigma_{eq} + k_s p)}{\sigma_{major} - \sigma_{minor}}$$



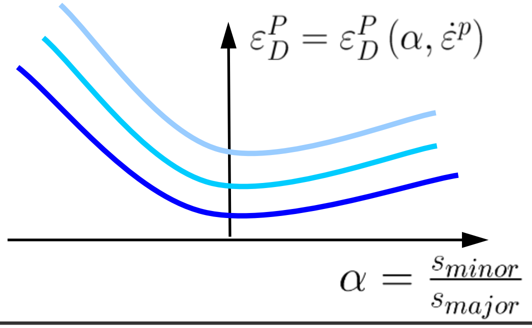
Instability

`DITYP=2` $\longrightarrow$ MSFLD
(no effect of compression)

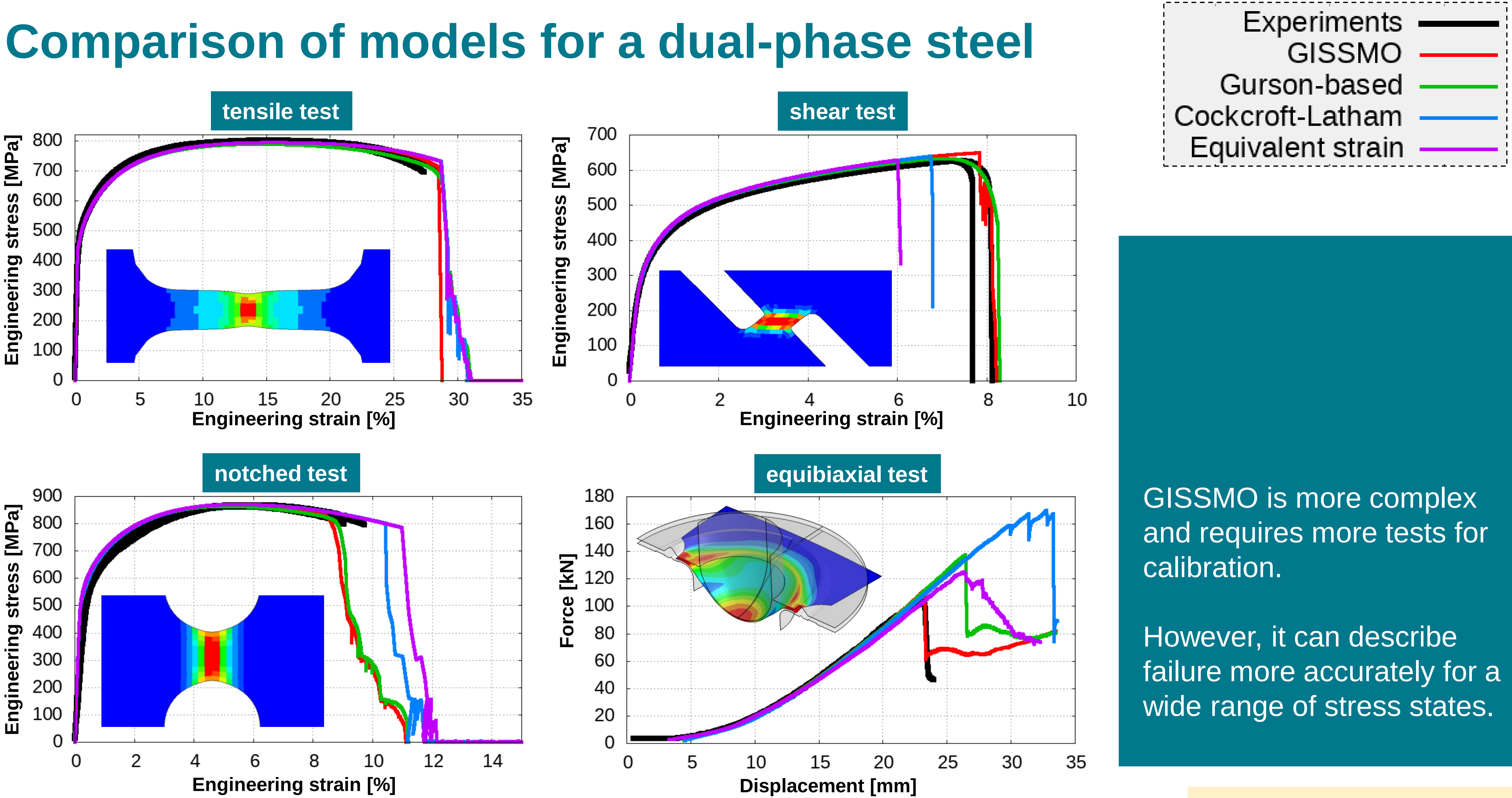
$$\omega_D^2 = \max_{t \le T} \frac{\varepsilon^p}{\varepsilon_D^p}$$

`DITYP=3` $\longrightarrow$ FLD

$$\omega_D^3 = \int_0^{\varepsilon^p} \frac{\mathrm{d}\varepsilon^p}{\varepsilon_D^p}$$



Comparison of models for a dual-phase steel

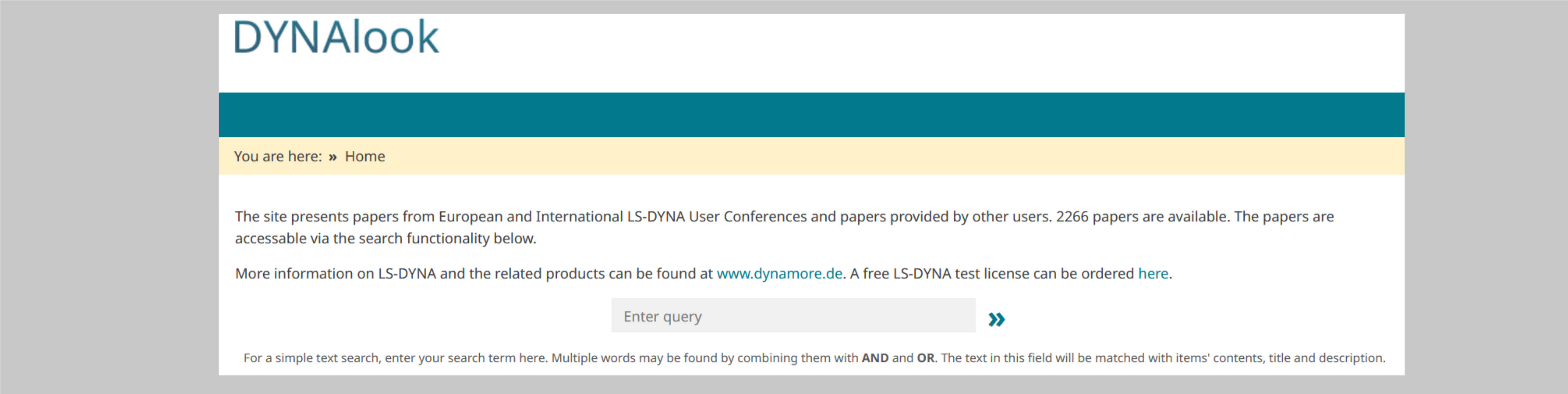


GISSMO is more complex and requires more tests for calibration.

However, it can describe failure more accurately for a wide range of stress states.

Where to get more information

- Classes from DYNAmore – https://www.dynamore.de/en/training/seminars
  - Modeling Metallic Materials
  - Material Failure
  - Advanced Damage Modeling: Orthotropic Materials
  - …
- LS-DYNA conferences, e.g., 16th LS-DYNA Forum 2022: www.dynamore.de/en/forum2022
- Papers at www.dynalook.com



The DYNAmore Material Competence Center (MCC)

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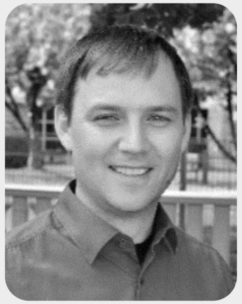
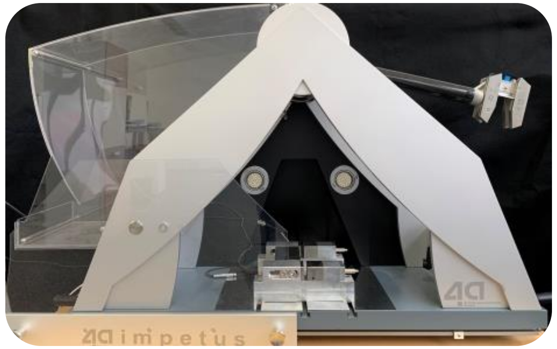

D. Koch


V. Suske

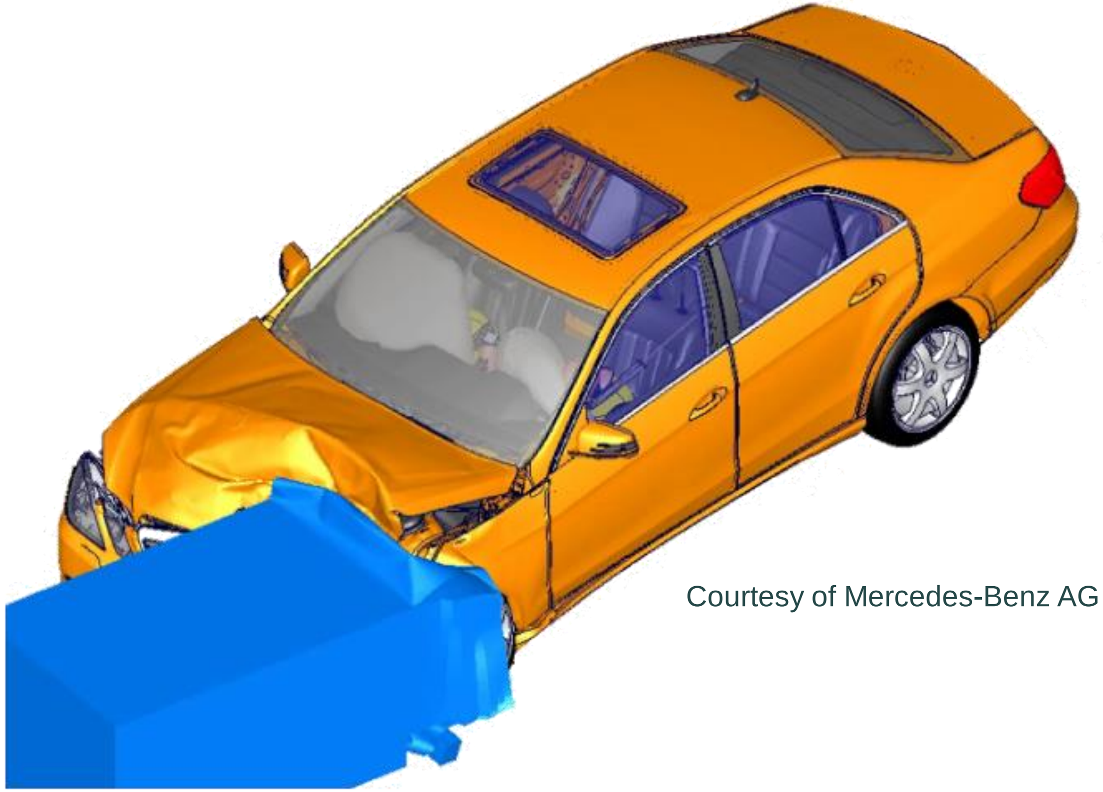

F. Kuzak


W. Feix

- Portfolio
  - Experimental material characterization and LS-DYNA material model calibration for: **Polymers, Glass, Foams & Metals**
  - Experiments
    - Tensile, bending, compression, punch test
    - Component testing
    - Local strain analysis with DIC (5M & 12M)
    - In house specimen cutting and preparation
  - Damage and fracture characterization and calibration for GISSMO and eGISSMO models



Thank You



Courtesy of Mercedes-Benz AG

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