Failure of Thermoplastics - Part 2
Material Modeling and Simulation

A. Fertschej, P. Reithofer, M. Rollant

4a engineering GmbH, Austria

1 Complex material models

Complex material models are much more used nowadays. The reasons are the increasing usage of plastics in high security relevance automotive and the resulting demand for virtual modeling including damage and failure. These complex material models allow a more detailed reproduction of reality, e.g. the tension/compression asymmetry. Implementing damage and failure is a time-consuming step and depends on the real material behavior but as well as on the testing method and on specific settings for the solver.

LS-Dyna offers many material models for plastics that have an implemented damage/failure modeling. This modeling goes from
- simple failure models (e.g. plastic strain, *MAT24)
- over comprehensive damage/failure models (e.g. plastic failure strain with damage, *MAT81)
- up to highly complex damage/failure models (e.g. failure in dependence of strain rate and triaxiality, *MAT_ADD_EROSION, see figure 1)

With the exception of *MAT187 (figure 2), which was developed especially for plastics, all these material resp. damage models were derived from the metals section. Anyway these models allow a good and technical suitable approximation to the reality of plastics. Just visco-elasticity and temperature dependency are neglected due to missing material models. Damage and failure can be included e. g. defined generally piecewise linear over triaxiality. Of course approaches describing the basic behavior of unreinforced plastics are still missing.

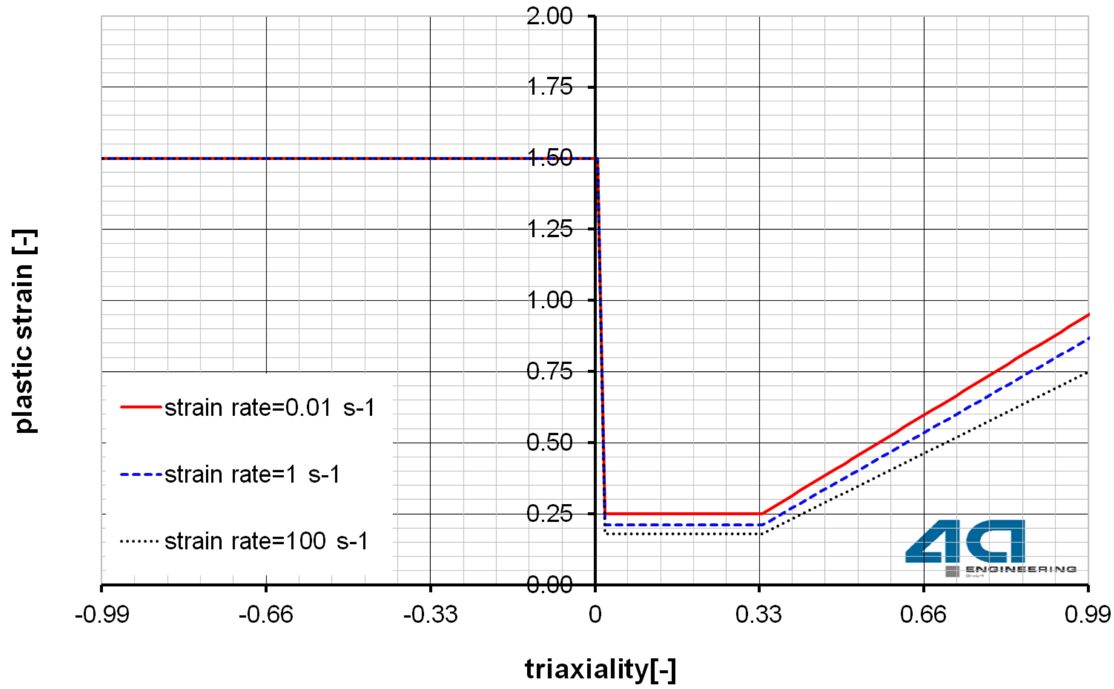


Fig.1: Example of failure curves in dependence of triaxiality and strain rate.

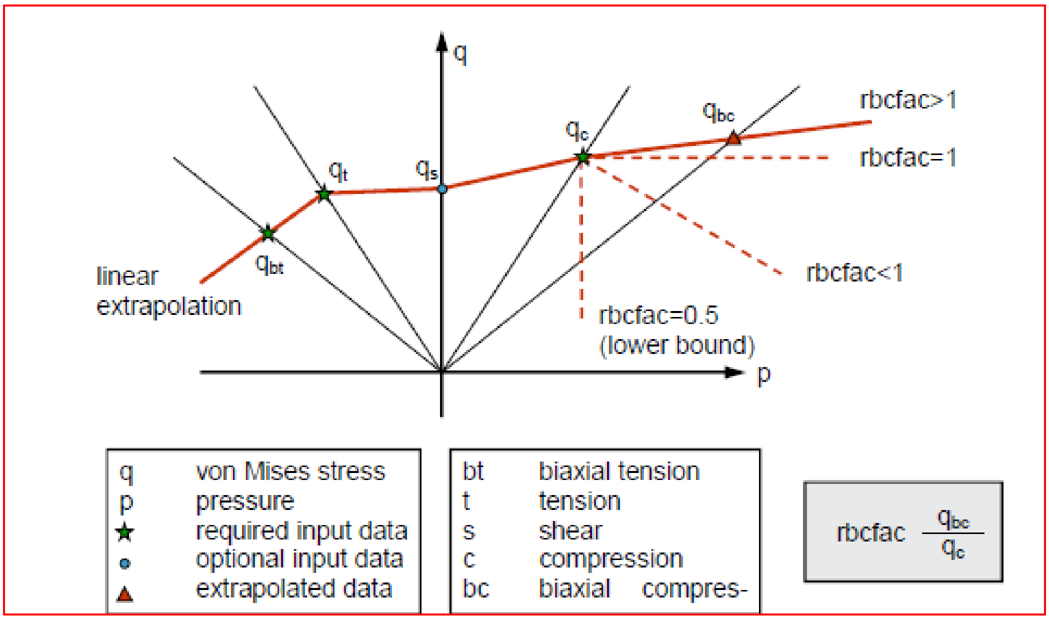


*Fig.2: von Mises stress as a function of pressure for *MAT187 [1].*

2 Material modeling and failure

When simulating crash or generally impact, failure (place and time) is essential for the development of the further load path and energy consumption. Because of increasing lightweight constructions plastics are carrying more and more the applied loads; therefore a comprehensive virtual modeling becomes more important. This situation is considered in the software of 4a impetus [2] by implementing some possibilities for modeling failure. So damage/failure in dependence of the load (triaxiality and strain rate) can be defined. Figure 3 shows exemplary a comparison of various failure models resp. failure settings of LS-Dyna, calculated in a one-element-test in 4a impetus.

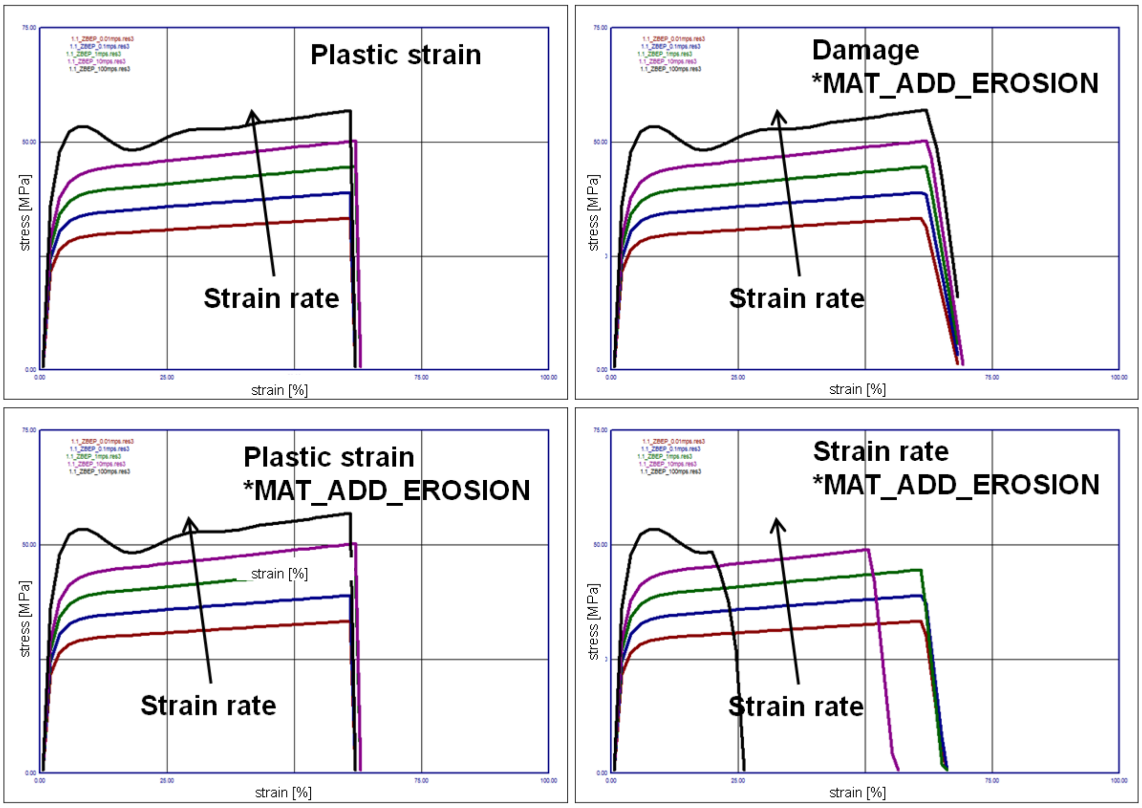


Fig.3: Results in stress/strain for using various failure models resp. settings [3].

The material characterization is done by reverse engineering using the 4a impetus process (figure 4). The material parameters are adapted iteratively until simulation and test fit with a minimum of deviation.

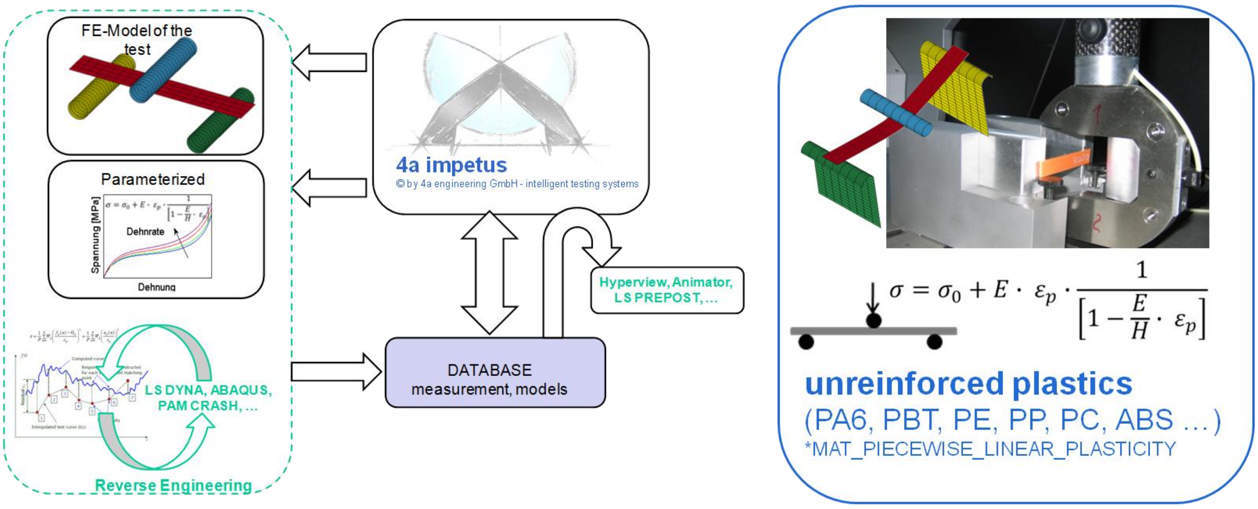


Fig.4: Material characterization by reverse engineering using the 4a impetus process [4].

Using a simple material model like *MAT24 the material behavior can be described very well for one triaxiality (typically tension is used). By using 3-point-bending tests (figure 5 left) a *MAT24 could be derived on a compression/tension average, which would cover most common applications in engineer's daily work. Nevertheless this approach can't describe the mechanical behavior of a tension dominated load cases (figure 5 right), which cannot be considered in the well known vonMises plasticity used in *MAT24.

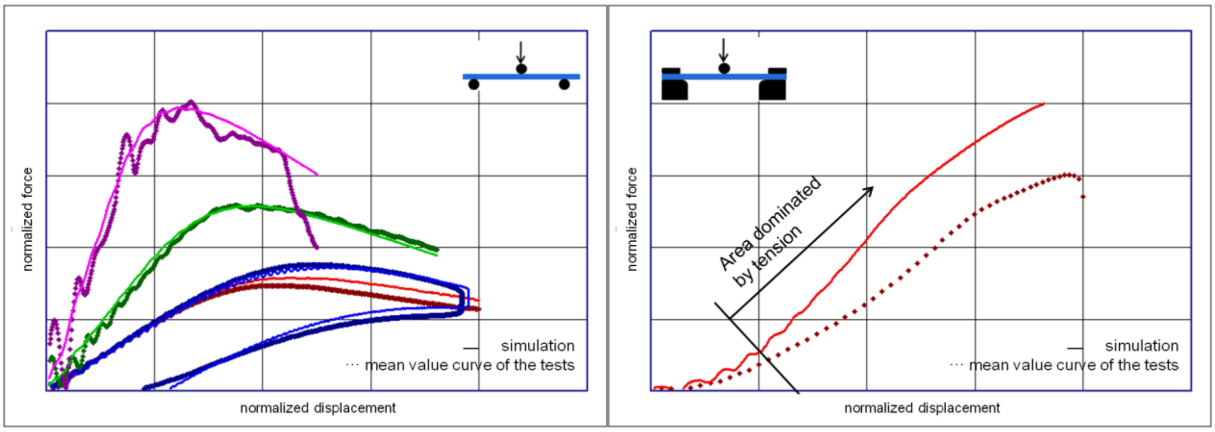


*Fig.5: left - Describing the material behavior using *MAT24 for bending tests at different velocities; test and simulation curves match very well.*
*right - Describing the material behavior using *MAT24 for the dynamic clamped bending test; test and simulation curve don't match because of the tension/compression asymmetry of the material which cannot be considered in the material model.*

So a more complex material model has to be used, e.g. *MAT187 (*MAT_SAMP-1), which considers such phenomena. This material model is also included in the software of 4a impetus.
Classically the material characterization would be performed on static tensile, shear and compression tests together with dynamic tensile tests. Nevertheless many steps have to be conducted to evaluate, transform and fit the test data to extract strain rate independent yield functions for different triaxialities (figure 6). These steps can be supported by using 4a impetus software (automatic reliable reproducible process). A first improvement can be

- the usage of static bending tests instead of compression tests and
- the usage of dynamic bending tests instead of dynamic tensile tests.

Figure 7 shows an alternative easy to use process:

- starting with static bending tests to get the yield function,
- deriving the strain rate dependency from dynamic bending tests,
- proving/reverse engineering the compression/tension asymmetry on clamped bending tests
- and finally validating further tests (figure 8 and 9).

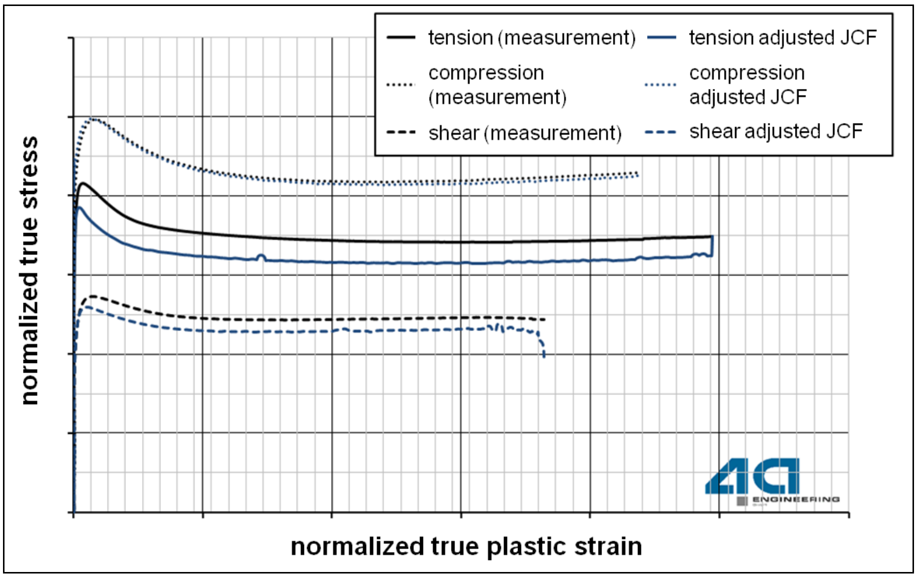


Fig.6: Comparison of original tensile/compression/shear measurement curves and measurement curves made independent of strain rate (strain rate dependency is determined by Johnson-Cook-Approach).

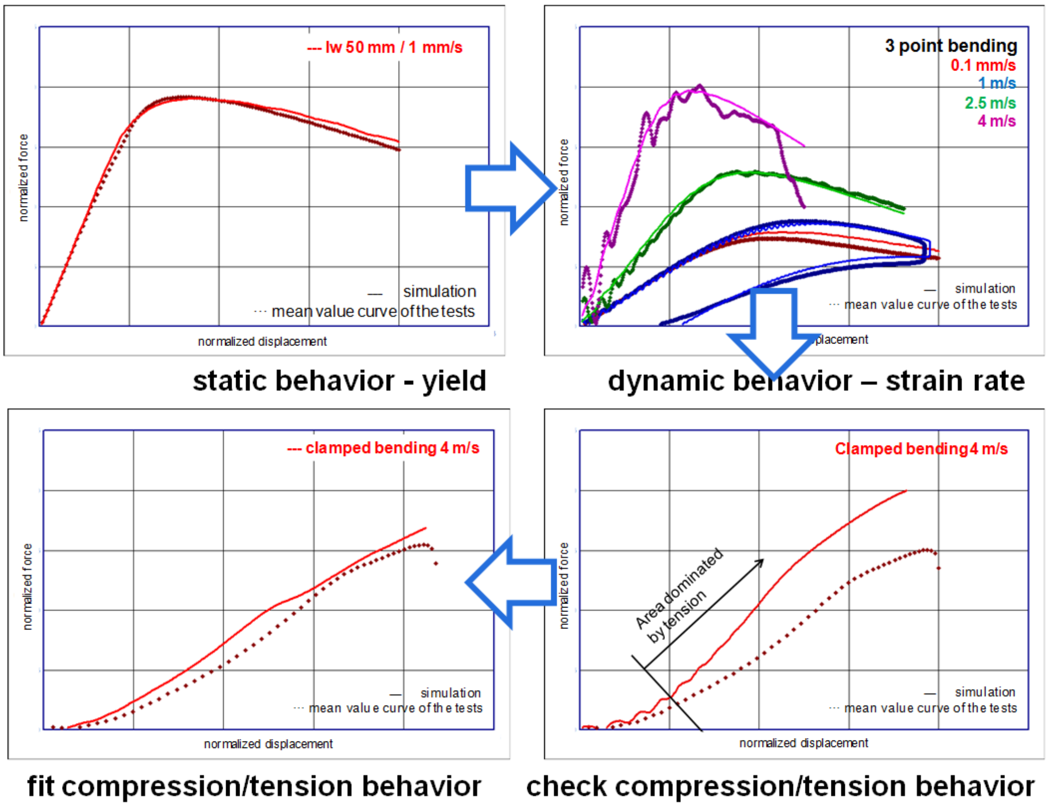


Fig.7: Improved workflow in 4a impetus to determine a complex yield surface.

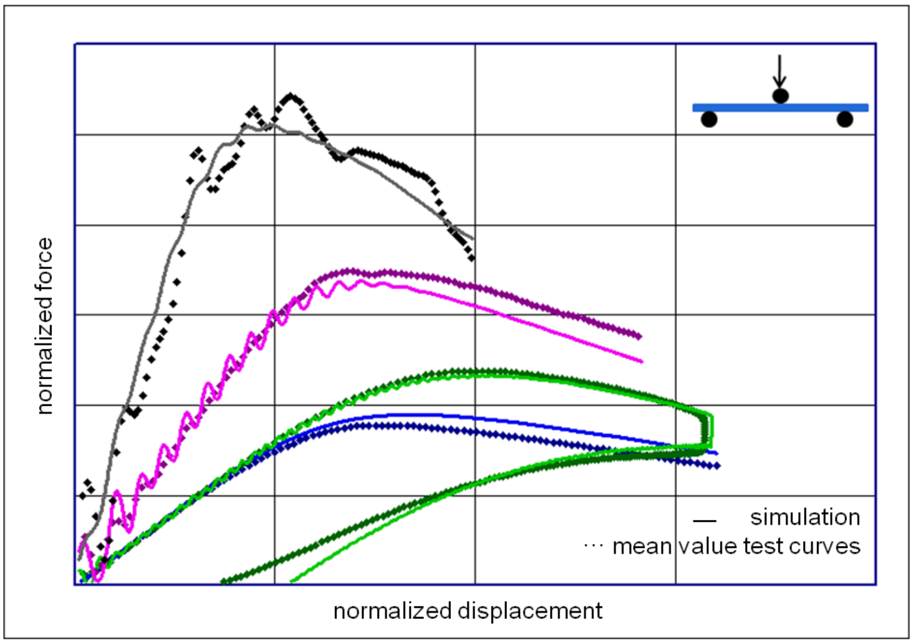


*Fig.8: Comparison of 3-point bending test curves at different velocities and simulation curves using *MAT187.*

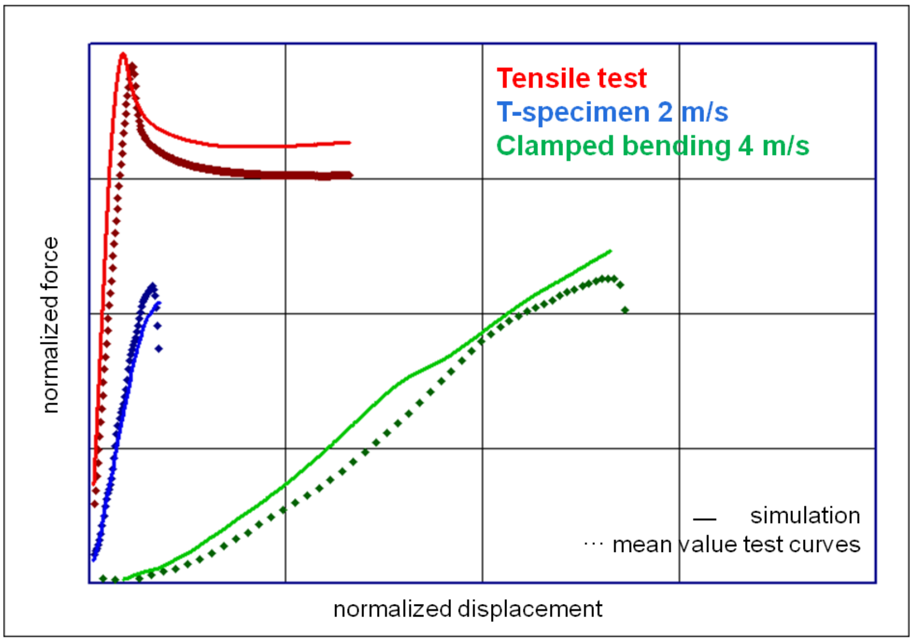


*Fig.9: Comparison of further test curves and simulation curves using *MAT187.*

Finally a damage/failure model has to be added to the material model. In this case the option *MAT_ADD_EROSION was chosen, within this option the Damage Initiation and Evolution Model DIEM [1] was used and adapted to the test curves.
In the end a final validation of this complex material model with damage and failure was performed for a part that was tested by a dynamic puncture test. Figure 10 shows the good conformity of simulation and test curves.

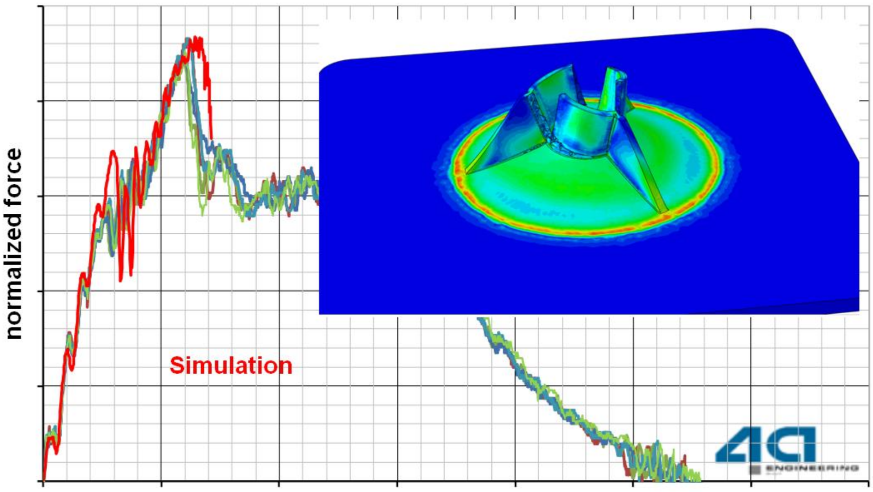


Fig.10: Comparison of test results to calculation results for a part characterized by a complex material model (test setup: dynamic puncture test).

3 Implementation in 4a impetus

An essential role in the simulation is the used idealization (shell vs. solid), element type and element size which have a significant influence on the calculation results. Figure 11 shows exemplary the influence of the element size on failure for various test velocities using *MAT24 with plastic strain as failure model; test setup was 3-point-bending. Such calculations can be done in 4a impetus just by changing the parameter (here: the element size) in the software interface.

In future a software supported workflow is the key enabler to the expected generation of complex material cards. Statistical methods have to be included to ensure the robustness in the usage of such complex material models. Both topics were considered in the past as well as they will be considered in the future in the testing system and the software 4a impetus.

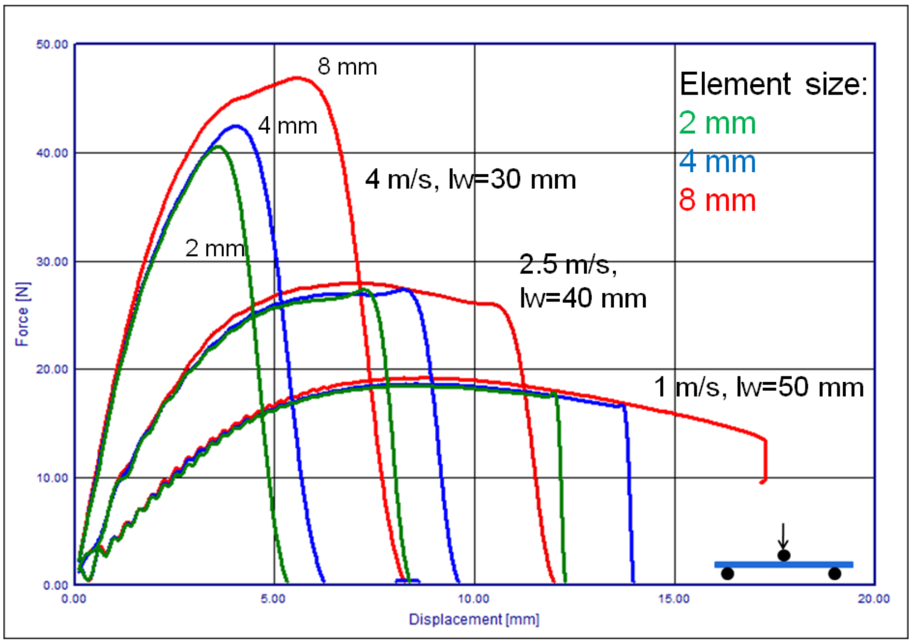


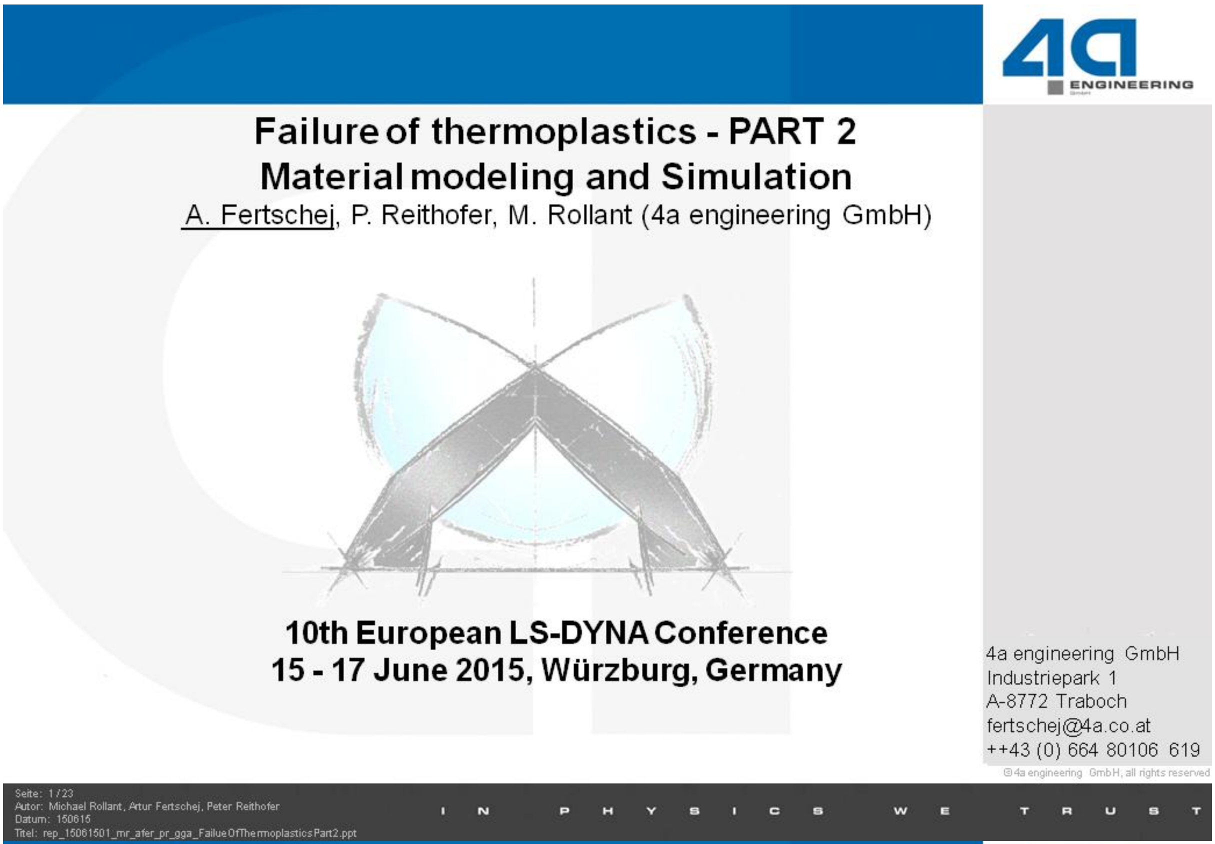
*Fig.11: Influence of the element size on failure for various test velocities in 3-point-bending (*MAT24, plastic strain as failure model; shell elements with 5 integration points) [5].*

4 Summary

Using static and dynamic 3-point-bending tests simple material cards (*MAT_24) are generated reasonable and quickly for simulation. If the material shows a tension/compression asymmetry the simple material model is limited, so more complex material models (e.g. *MAT_SAMP-1) are needed.
Additional tests (tension, shear, compression, etc.) for such models can be imported into 4a impetus and used for material characterization and modeling.
A novel workflow based on standard 4a impetus test methods has been shown to generate complex material cards like *MAT_SAMP-1. It was shown that *MAT_ADD_EROSION offers all needed possibilities to describe the failure behavior of unreinforced thermoplastics close to reality.
4a impetus has been and is upgraded by including failure modeling using various failure models to meet these requirements for an accurate material modeling.

5 Literature

[1] LS-DYNA© KEYWORD USER'S MANUAL - VOLUME II - Material Models
[2] http://impetus.4a.co.at/en/
[3] A. Fertschej, P. Reithofer, M. Rollant (4a engineering GmbH) - Materialmodelle für Kunststoffe, Komplexe Fließflächen und Versagen; 4a Technologietag 2014, Schladming
[4] P. Reithofer, M. Rollant (4a engineering GmbH) - Dynamische Materialcharakterisierung mit 4a impetus; 4a Technologietag 2012, Schladming
[5] A. Fertschej, P. Reithofer, M. Rollant (4a engineering GmbH); A. Förderer, V. Effinger (Dynamore GmbH) - Workshop „Plastics“, 13. LS-DYNA Anwenderforum 2014, Bamberg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A. Fertschej, P. Reithofer, M. Rollant (4a engineering GmbH)
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4a engineering GmbH
Industriepark 1
A-8772 Traboch
fertschej@4a.co.at
++43 (0) 664 80106 619
© 4a engineering GmbH, all rights reserved
Seite: 1 / 23
Autor: Michael Rollant, Artur Fertschej, Peter Reithofer
Datum: 150615
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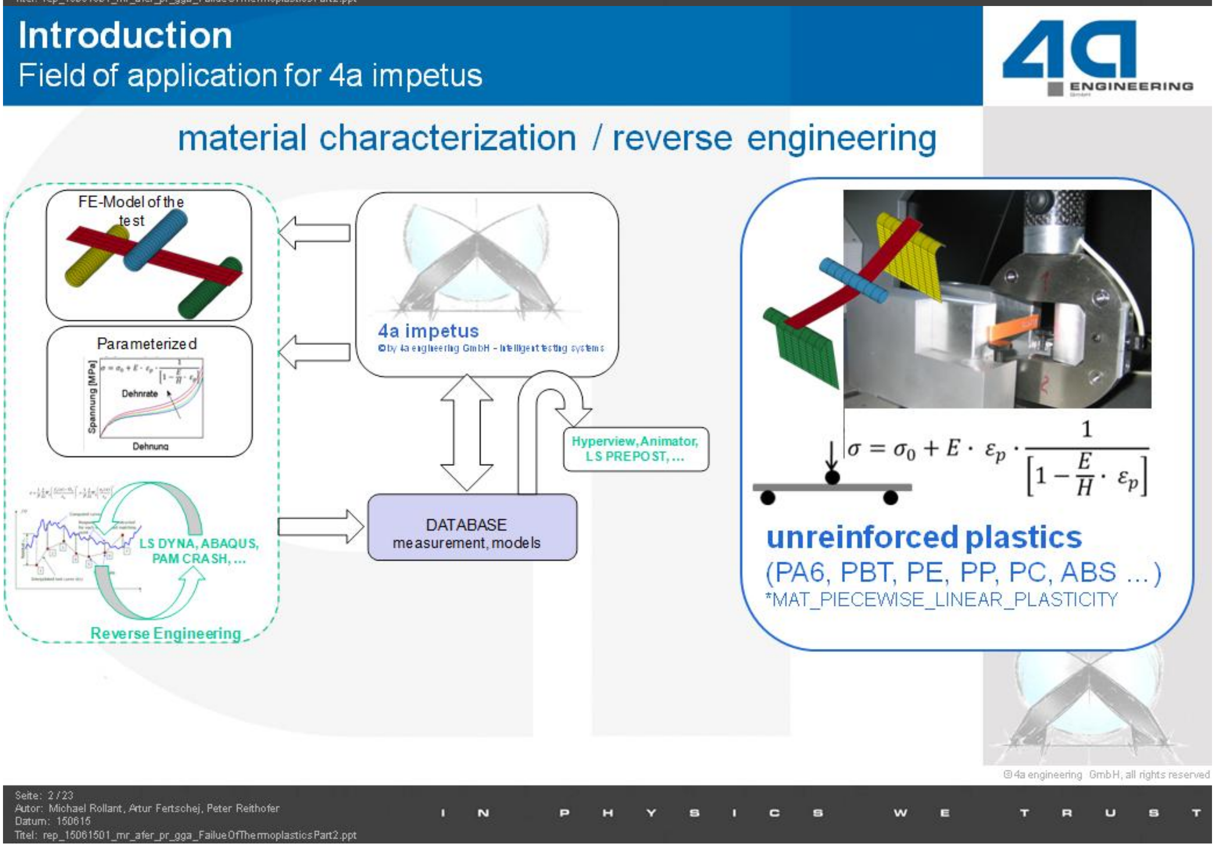
I N P H Y S I C S W E T R U S T


Introduction
Field of application for 4a impetus
material characterization / reverse engineering
FE-Model of the test
Parameterized
Spannung [MPa]
Dehnrate
Dehnung
LS DYNA, ABAQUS, PAM CRASH, ...
Reverse Engineering
4a impetus
© by 4a engineering GmbH - intelligent testing systems
Hyperview, Animator, LS PREPOST, ...
DATABASE
measurement, models
$\sigma = \sigma_0 + E \cdot \varepsilon_p \cdot \frac{1}{\left[1 - \frac{E}{H} \cdot \varepsilon_p\right]}$
unreinforced plastics
(PA6, PBT, PE, PP, PC, ABS ...)
*MAT_PIECEWISE_LINEAR_PLASTICITY
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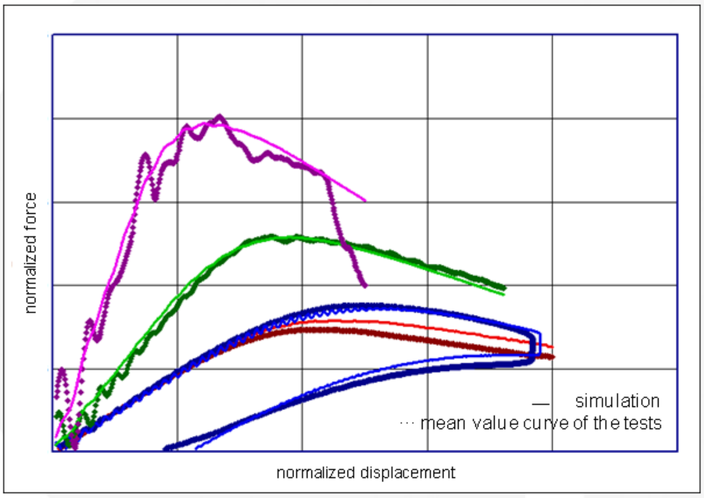
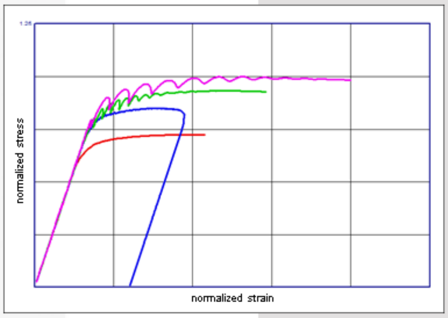
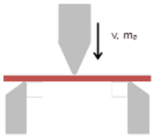
Autor: Michael Rollant, Artur Fertschej, Peter Reithofer
Datum: 150615
Titel: rep_15061501_mr_afer_pr_gga_FailueOfThermoplasticsPart2.ppt
I N P H Y S I C S W E T R U S T

Introduction
Reverse engineering, *MAT_24

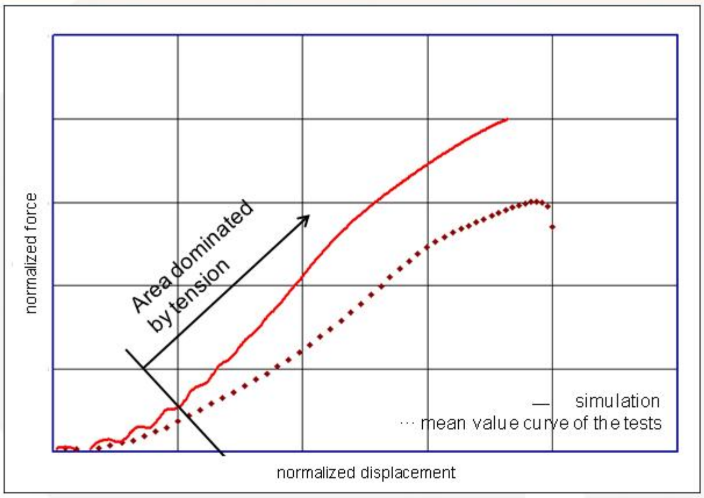


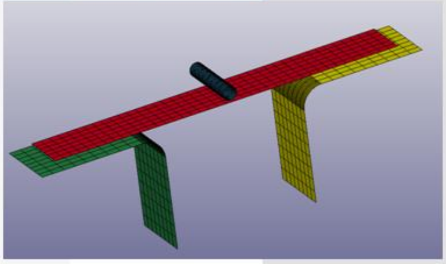




For the isotropic elastic viscoplastic material model (*MAT_24 in LSDYNA) a material model considering strain rate dependency was determined by reverse engineering for the conducted static and dynamic 3-point-bending tests. The optimization can reproduce the mechanical behavior very good.

Introduction
Validation clamped 3-point-bending test, *MAT_24





The simulation provides for the load case clamped 3-point-bending test a behavior that is too stiff in the area which is dominated by tension. In this area the used material model reaches its limits.

Available material models for plastics
Status of the interfaces in 4a impetus V3.2

- Currently implemented models for LS-DYNA
  - MAT_19: *MAT_STRAIN_RATE_DEPENDENT_PLASTICITY — von Mises
  - MAT_24: *MAT_PIECEWISE_LINEAR_PLASTICITY — von Mises
  - MAT_124: *MAT_PLASTICITY_COMPRESSION_TENSION — Drucker Prager
  - MAT_187: *MAT_SAMP-1 — gen. yield surface

Material behaviour	
Material source	Implemented
Density	1020.81
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	vonMises
Curve 1	4a Model A
Strain rate dependency	Table
Strain rate dependency	Johnson Cook
Strain range upto	0.15
Sampling points	50
Bias factor	10
Material card	7011_MAT24_Plasticity Table Rate log. Table

Material behaviour	
Material source	Implemented
Density	1020.81
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	Drucker-Prager
Curve 1	4a Model A
Curve 2	Kurve 1 skaliert
Strain rate dependency	Table
Strain rate dependency	Johnson Cook
Strain range upto	0.15
Sampling points	50
Bias factor	10
Material card	7021_MAT124

Material behaviour	
Material source	Implemented
Density	1020.81
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	general yield surface (3 curves)
Curve 1	4a Model A
Curve 2	Kurve 1 skaliert
Curve 3	Kurve 1 skaliert
Strain rate dependency	Table
Strain rate dependency	Johnson Cook
Strain range upto	0.15
Sampling points	50
Bias factor	10
Material card	7031_MAT187

- All LS-DYNA material cards are available by user defined interfaces

Adaption of general yield surface
Adaption *MAT_SAMP-1

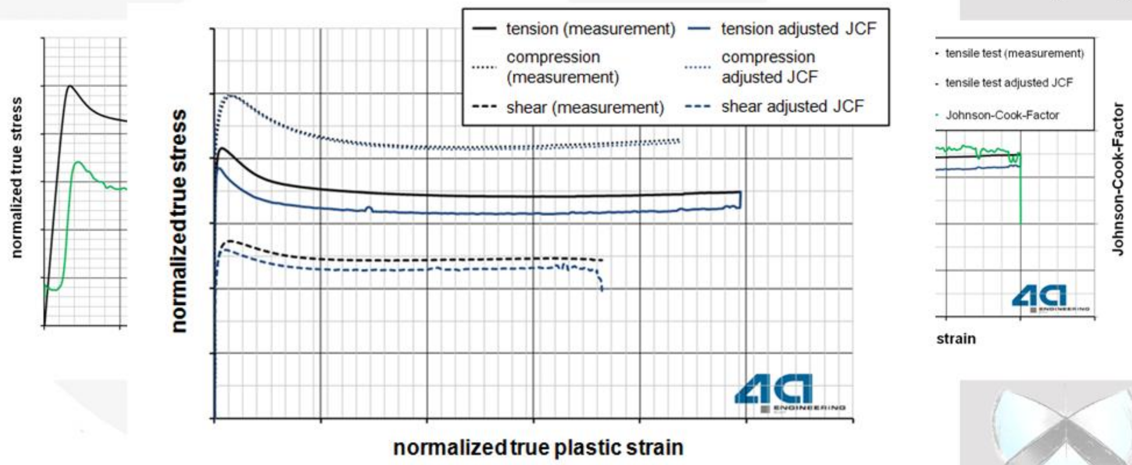
Two ways to adapt the general yield surface:

- Classic approach: using static tensile, shear and compression tests together with dynamic tensile tests
  - many steps to extract strain rate independent yield functions for different triaxialities

Adaption of general yield surface
Adaption *MAT_SAMP-1

- Tensile/compression/shear curves are made independent of the strain rate (strain rate dependency is determined by Johnson-Cook-Approach)

$$1+\frac{1}{C}\cdot\log\left(\frac{\max(\dot{\varepsilon},\dot{\varepsilon}_{ref})}{\dot{\varepsilon}_{ref}}\right)$$



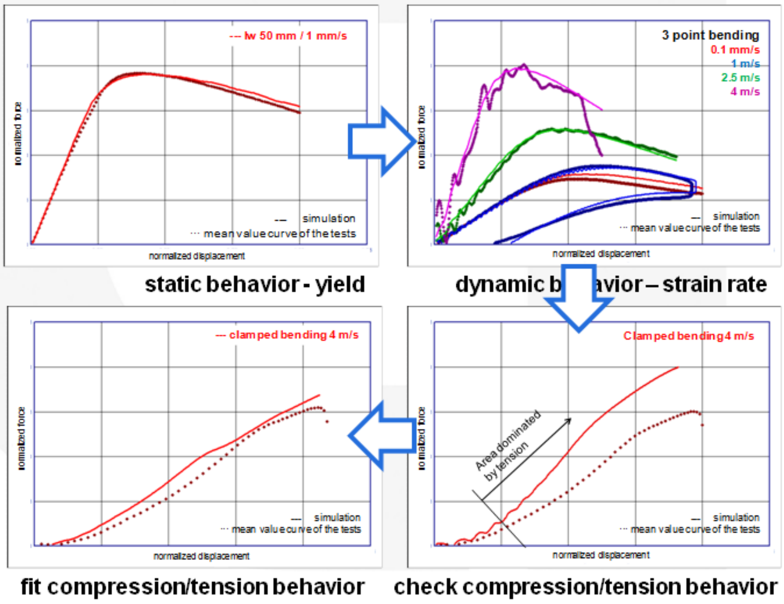
Adaption of general yield surface
Adaption *MAT_SAMP-1

Two ways to adapt the general yield surface:

- 4a impetus approach:
  - Using static bending tests instead of compression tests
  - using dynamic bending tests instead of dynamic tensile tests

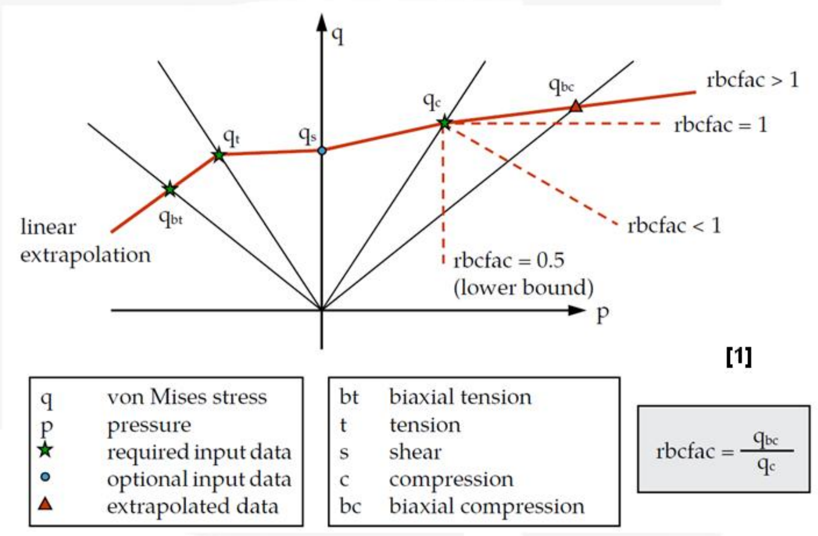
Adaption of general yield surface
Adaption *MAT_SAMP-1

Reverse Engineering 4a impetus



Adaption of general yield surface
Adaption *MAT_SAMP-1

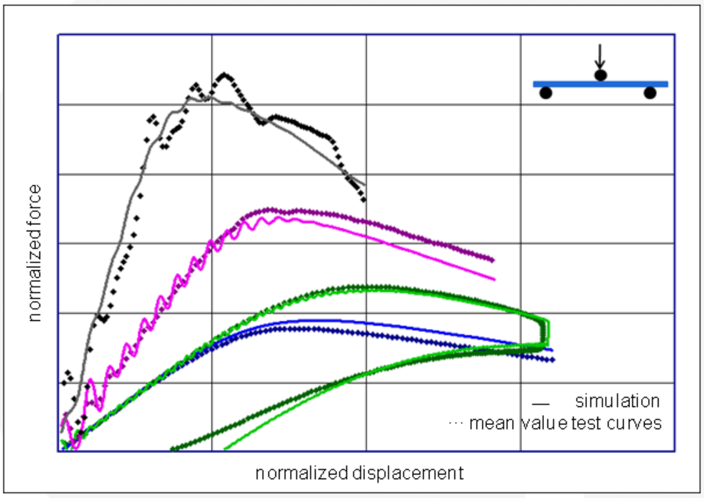
General yield surface:



[1] LS-DYNA® KEYWORD USER'S MANUAL - VOLUME II - Material Models

Adaption of general yield surface

Validiation bending tests, *MAT_SAMP-1

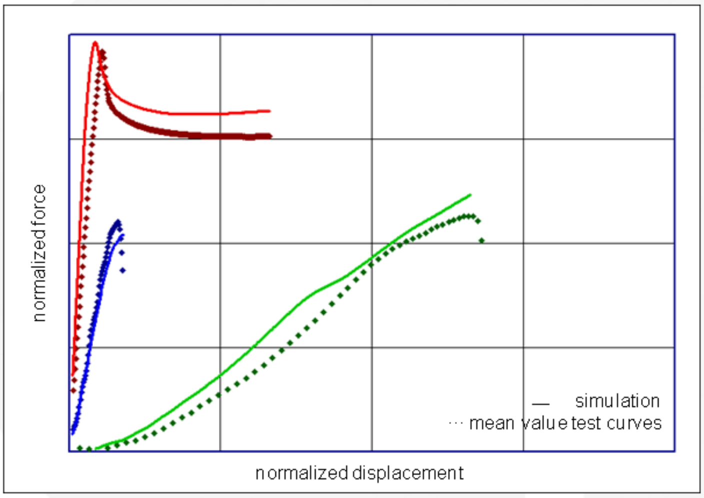


0.1 mm/s
1 m/s
2.5 m/s
4 m/s

Using the material model of a general yield surface the bending tests can be simulated very good. Failure was not considered yet.

Adaption of general yield surface

Validation tensile test, T-specimen, clamped bending, *MAT_SAMP-1



Tensile test
T-specimen 2 m/s
Clamped bending 4 m/s

Also the results for the tensile test, the T-specimen and the clamped bending are now very good. Of course, failure was not considered again.

Possibilities to model failure
Available failure resp. damage models in LS-DYNA

- plastic equivalent strain
  e.g. **MAT_24:** **MAT_PIECEWISE_LINEAR_PLASTICITY*
- plastic equivalent strain including damage
  e.g. **MAT_81:** **MAT_PLASTICITY_WITH_DAMAGE*
- strain rate dependent equivalent criterion
  e.g. **MAT_19:** **MAT_STRAIN_RATE_DEPENDENT_PLASTICITY*
  or **MAT_124:** **MAT_PLASTICITY_COMPRESSION_TENSION*
- equivalent criterion in dependence of the triaxiality, …
  z.B. **MAT_187:** **MAT_SAMP-1*

As alternative the additional option *MAT_ADD_EROSION* in combination with the material card offers a multitude of possible damage and failure modeling.

Possibilities to model failure
User defined material card / *MAT_ADD_EROSION

- The card **MAT_ADD_EROSION* is added to an already existing card,
  e.g. *MAT_187:

```
*MAT_ADD_EROSION
$     MID      EXCL   MXPRES    MNEPS   EFFEPS   VOLEPS   NUMFIP     NCS
  1000000
$  MNPRES     SIGP1    SIGVM    MXEPS    EPSSH    SIGTH   IMPULSE   FAILTM

$    IDAM    DMGTYP    LCSDG    ECRIT   DMGEXP    DCRIT   FADEXP   LCREGD
       -1         1
$   DITYP        P1       P2
        0    100005        0
$   DETYP     DCTYP       Q1
        1                0.1
$==========================================
*DEFINE_CURVE
$ P1
$    lcid      sidr     scla     sclo     offa     offo   dattyp
   100005         0      1.0      1.0
$               x                 y
        -1.000000      1.0000000000
         0.000000      0.0400000000
         0.330000      0.0600000000
         0.660000      0.0800000000
         1.000000      0.1000000000
```

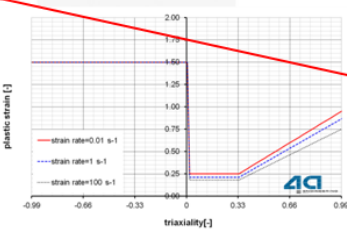
Same ID as in *MAT_187

1 Damage Initiation and Evolution criterion (DIEM)
As alternative: GISSMO

Ductile damage initiation
Further alternatives: shear and instability criterion (MSFLD)

Damage initiation parameter: Triaxiality vs. plast. strain

Damage evolution parameter

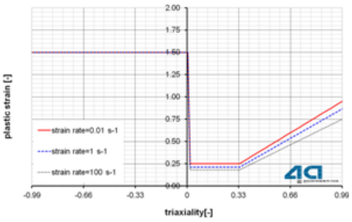


Possibilities to model failure
User defined material card / *MAT_ADD_EROSION

- Failure can be made dependent on the strain rate:

```
*DEFINE_TABLE
$#   tbid
 100005
$#        value       lcid
          0.001    1000011
            100    1000012
*DEFINE_CURVE
$     lcid     sidr     scla     sclo     offa     offo   dattyp
 1000011        0      1.0      1.0
$               x                y
        -1.000000      1.0000000000
         0.000000      0.0400000000
         0.330000      0.0600000000
         0.660000      0.0800000000
         1.000000      0.1000000000
$==========================================
*DEFINE_CURVE
$     lcid     sidr     scla     sclo     offa     offo   dattyp
 1000012        0      1.0      1.0
$               x                y
        -1.000000      1.0000000000
         0.000000      0.0200000000
         0.330000      0.0400000000
         0.660000      0.0600000000
         1.000000      0.0800000000
```

Strain rates



Adaption *MAT_ADD_EROSION
DIEM-Model

- DIEM: Damage Initiation and Evolution Model [1]
- Base: Standard material model (e.g. *MAT_187)
- 3 individual criteria can be used:
  - Ductile criterion: $\varepsilon_D^{\,P} = \varepsilon_D^{\,P}(\eta, \dot{\varepsilon}^p)$
  - Shear criterion: $\varepsilon_D^{\,P} = \varepsilon_D^{\,P}(\theta, \dot{\varepsilon}^p)$

  $$\omega_D = \int_0^{\varepsilon^P} \frac{d\varepsilon^P}{\varepsilon_D^{\,P}}$$

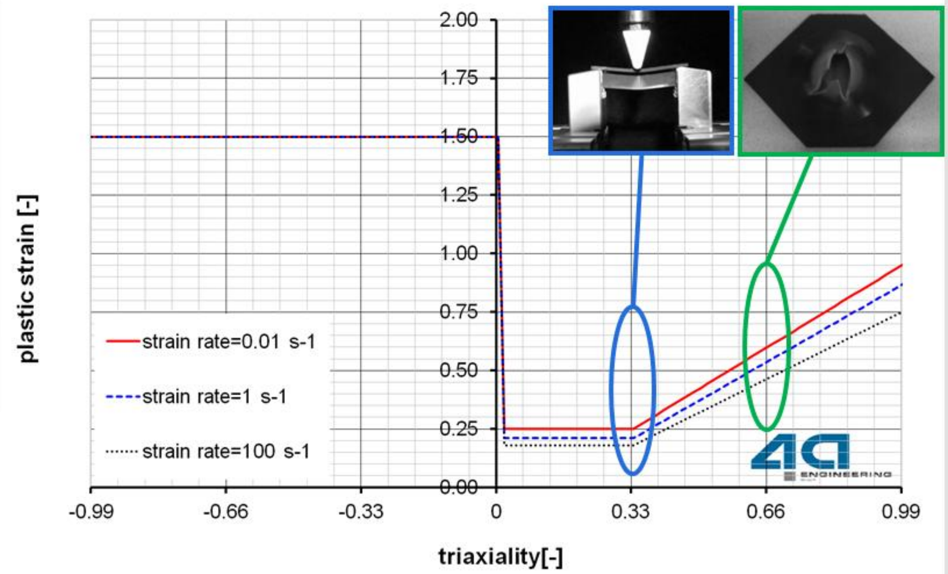
  - Instability criterion: $\varepsilon_D^{\,P} = \varepsilon_D^{\,P}(\alpha, \dot{\varepsilon}^p)$ $\quad \alpha = \frac{\dot{\varepsilon}^{\,P}_{\min\ or}}{\dot{\varepsilon}^{\,P}_{major}}$ $\longrightarrow$ $\omega_D = \max \frac{\varepsilon^P}{\varepsilon_D^{\,P}}$
- After initiation the damage evolution occurs:

$$\sigma = (1-D)C^{ep} : \varepsilon$$

[1] LS-DYNA® KEYWORD USER'S MANUAL - VOLUME II - Material Models

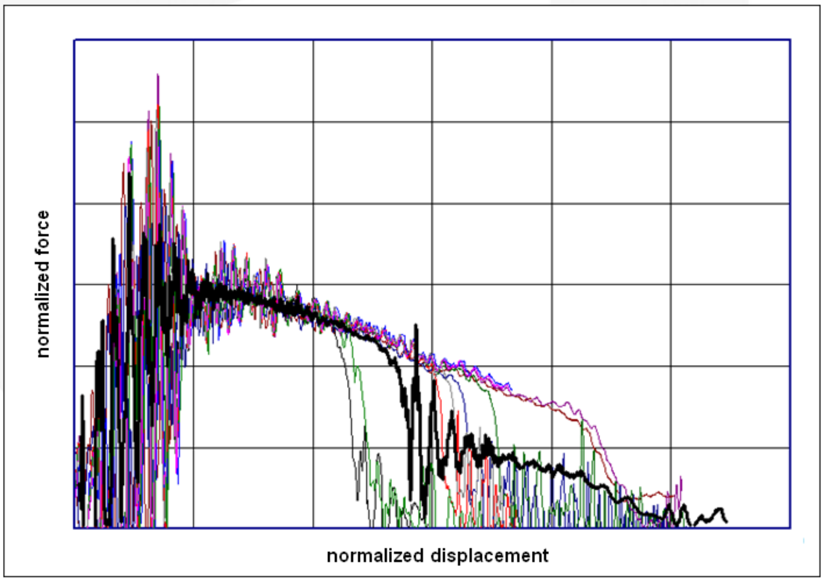
Adaption *MAT_ADD_EROSION
DIEM-Model

- Evaluation of the failure strains



Validation
* MAT_SAMP-1 with *MAT_ADD_EROSION

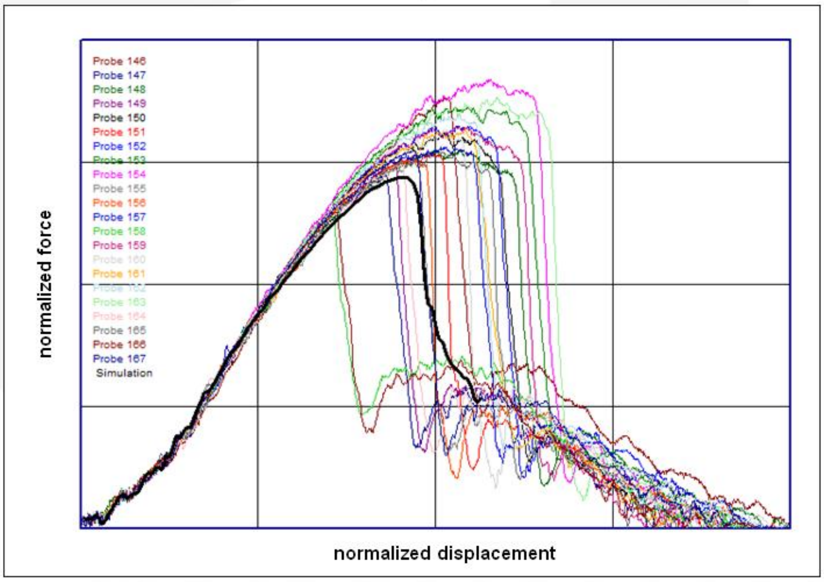
- 3-point-bending, 4 m/s, unfiltered
- The test curves are matched very well.



Colored: Test curves
Black: Simulation

Validation
* MAT_SAMP-1 with *MAT_ADD_EROSION

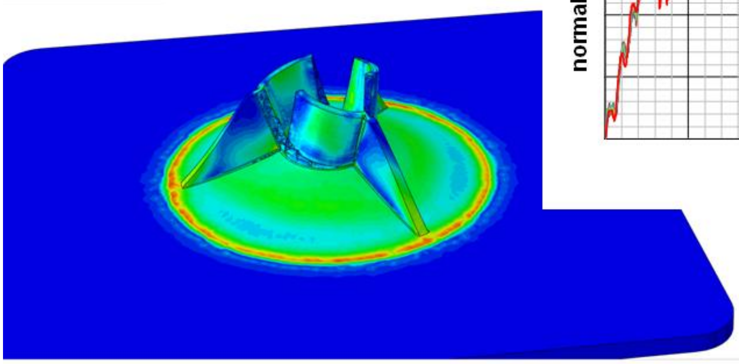
- Dynamic puncture test
- The test curves are matched very well.

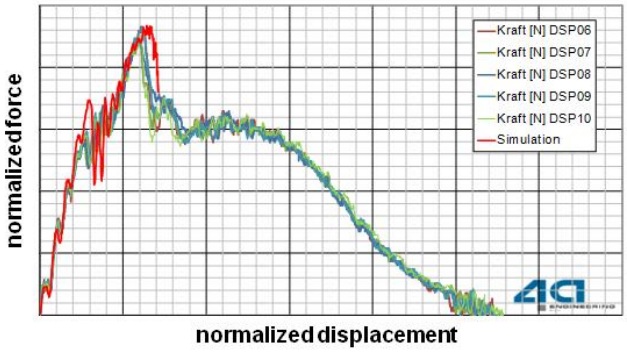


Colored: Test curves
Black: Simulation

Validation
* MAT_SAMP-1 with *MAT_ADD_EROSION

- Dynamic puncture test with the part
- The test curves are matched very well.





Summary

4a ENGINEERING

- Using static and dynamic 3-point-bending tests simple material cards (*MAT_24) are generated reasonable and quickly for simulation.
- If a tension/compression asymmetry occurs the simple material model is limited, so more complex material models (e.g. *MAT_SAMP-1) are needed.
- Additional tests (tension, shear, compression, ...) for e.g. *MAT_SAMP-1 can be imported into 4a impetus and used for material characterization and modeling.
- Implementing a damage and failure model (*MAT_ADD_EROSION) the used material can be reproduced best possible and close to reality.
- 4a impetus is upgraded by including failure modeling using various failure models at the moment.

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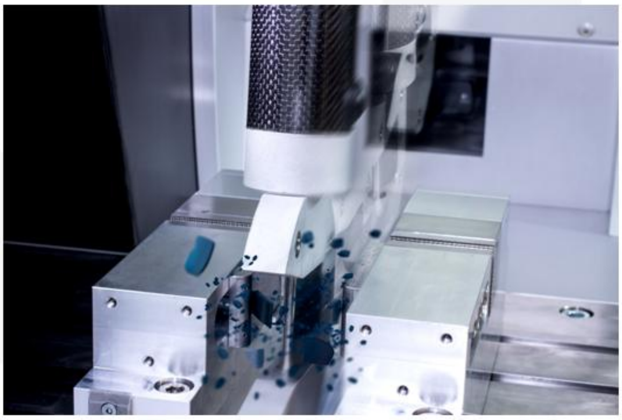
Workshop „Dynamic Plastic Material Characterization using the 4a impetus Pendulum“
Wednesday, 17th June, 8:30

More information about 4a impetus
Live demonstration

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