Validation and Material Modelling of Plastics

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Summary:
The virtual estimation of physical product properties is only as good as the virtual description of the behaviour of its material. On the one hand there are well known material cards like *MAT_PIECEWISE_LINEAR_PLASTICITY in LS-DYNA© developed to describe a simplified behaviour of metallic materials. The reduced complexity of these material cards makes it possible to determine its parameters with less effort in actual material testing. Main advantages are high numerical stability and less machine time.
On the other hand complex material models like *MAT-SAMP-1 can also handle varying compression and tension behaviours by defining a load case dependent yield surface as well as unloading by using damage functions. With the exception of visco-elasticity the description of visco-plasticity fulfills many requirements to describe a realistic behaviour of thermoplastics. For acceptable use of the above mentioned models a higher amount of load cases like tension, compression, shear have to be carried out to determine the material parameters and to represent the thermoplastic characteristics in crashworthiness simulations.
At the moment there is no standardized method to determine material card properties for arbitrary material models from basic (i.e. tension, compression or shear) test setups.
4a impetus represents a standardized method, an efficient and reliable process starting with realistic test scenarios and finally ending up with a validated material card. The method of reverse engineering is used behind this process to generate material cards like *MAT_PIECEWISE_LINEAR_PLASTICITY as well as more complex *MAT_PLASTICITY_COMPRESSION_TENSION with regard to easy and favourable testing.
We have compared different ways to determine and validate material cards with the example of PA6. Limits and opportunities of different test methods and material card implementations are shown and compared to each other especially focused on typical polymer behaviour.

Keywords:
Thermoplastics, Polyamide, PA6, Material Modelling, Validation, 4a Impetus, *MAT_PIECEWISE_LINEAR_PLASTICITY, *MAT_PLASTICITY_COMPRESSION_TENSION, *MAT_SAMP_1, Reverse Engineering

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STRASBOURG - France

content

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- polymer materials (influences , general behavior)
- classical approach for measurement of thermoplastics
- motivation – material variety case studies
- motivation – bending load case
- 4a Impetus
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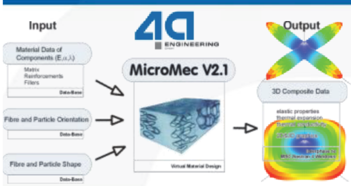
  - dynamic tests
  - graphical user interface
  - typical simulation models
  - reverse engineering
  - Implemented modells
- Material Card Generation
  - Comparison & Validation
- efford
- conclusion

division: 4a engineering GmbH

- R&D and engineering services
- core competence
  - polymer- and materials science
  - numerical simulation methods
  - lightweight applications
  - fiber reinforced plastics and composites
  - method development for virtual engineering
- 15 to 20 key customers
- more than 500 projects
  - 45% automotive
  - 15% aerospace
  - 15% mechanical engineering
  - 10% medical engineering
  - 15% consumer goods

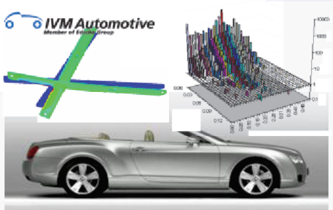
in physics we trust

method development
virtual competence in complex materials

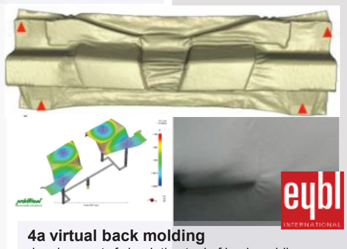


4a micromechanical modelling
micro mechanical software solution – micromec®
for calculating thermo-mechanical
properties of composites

4a virtual fibermapping
prediction of orientation based stiffness and
strengths of short and long fiber reinforced plastics
in the static and dynamic structural simulation



4a fatigue - composites
linear cumulative damage analysis
failure prediction by Puck´s criteria
consideration of anisotropic lay-up



4a virtual back molding
development of simulation tool of back molding
process in textile applications in the field of
automotive interiors→ prediction of product behavior


product development
lightweight applications / polymers and composites
4a ENGINEERING
MAGNA STEYR
LH$_2$ – inner tank suspension
lowest possible heat transfer / BMW clean energy
high stiffness, high strength composite solution
increased performance : 250%
Mobile phone speaker
high frequency, high stiffness , low weight
brilliant sound quality
2007: 10% global market share
Binding for back country skiing
development of the world´ s lightest binding
for ski touring, reduction of weight: 40%
compared to the previous model
4a multi layer composite
high potential for light weight applications
20% weight reduction – carbon fiber reinf. plastics
70% weight reduction compared to polypropylene
FISCHER
Resin transfer molded carbon brace
substitution of steel brace by RTM carbon brace
with a carbon fiber reinforced plastic – solution
60 % weight reduction
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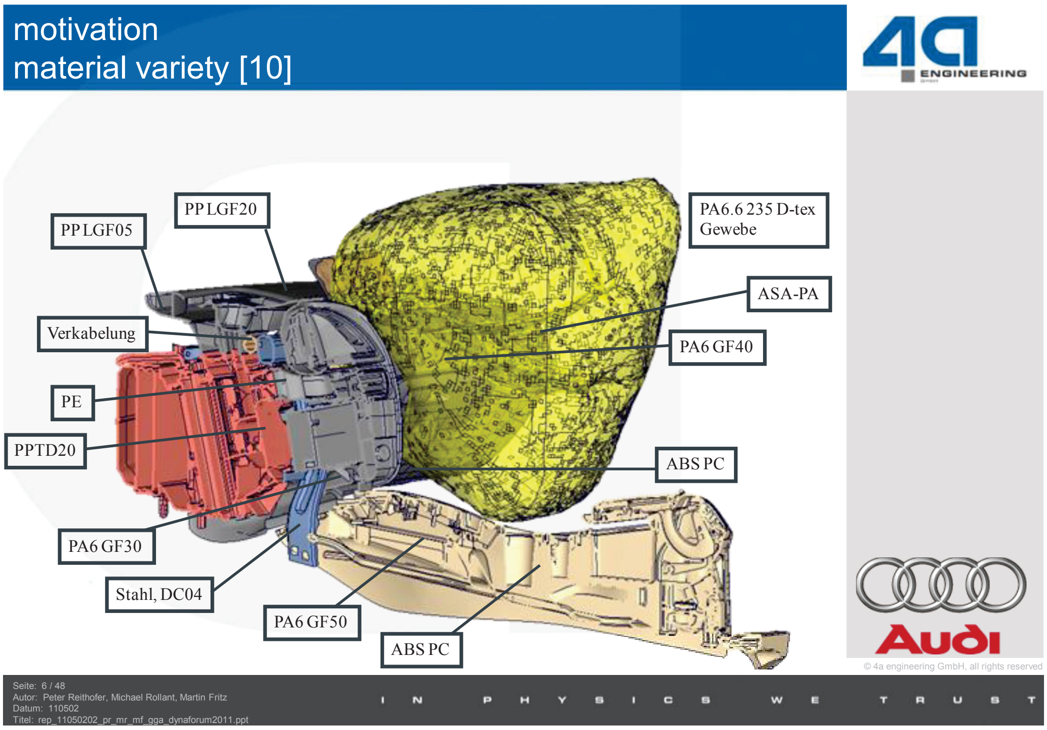
motivation
material variety [10]
4a ENGINEERING
PP LGF05
PP LGF20
PA6.6 235 D-tex Gewebe
ASA-PA
Verkabelung
PA6 GF40
PE
PPTD20
ABS PC
PA6 GF30
Stahl, DC04
PA6 GF50
ABS PC
Audi
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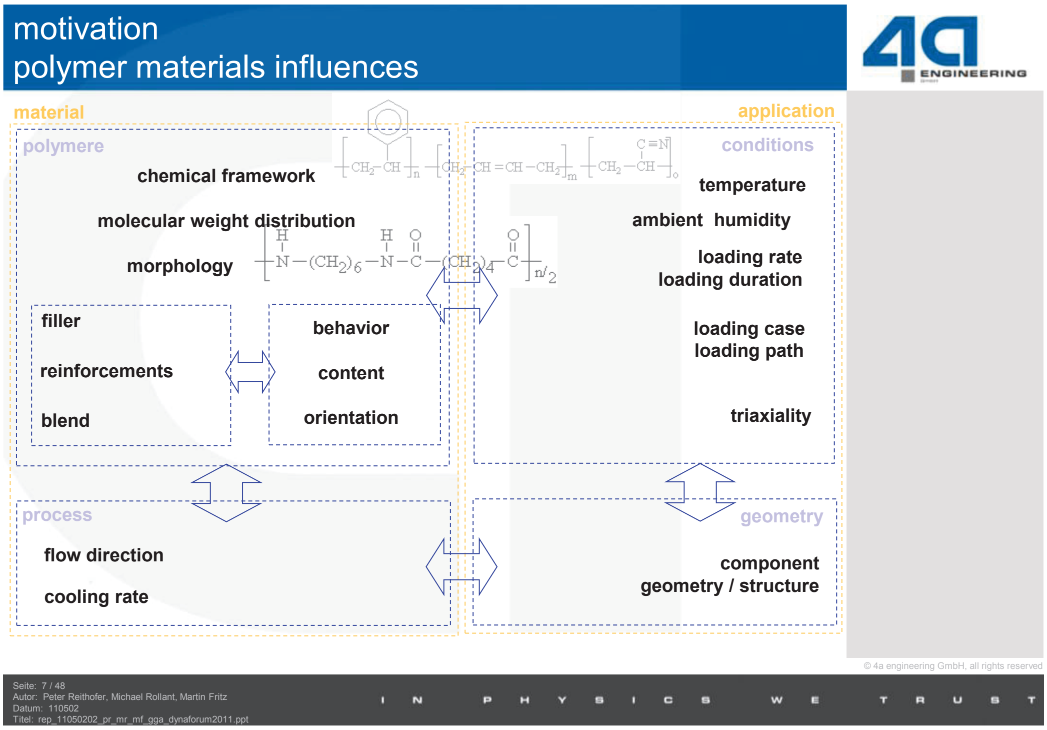
motivation
polymer materials influences
material
application
polymere
chemical framework
molecular weight distribution
morphology
filler
reinforcements
blend
behavior
content
orientation
conditions
temperature
ambient humidity
loading rate
loading duration
loading case
loading path
triaxiality
process
flow direction
cooling rate
geometry
component
geometry / structure
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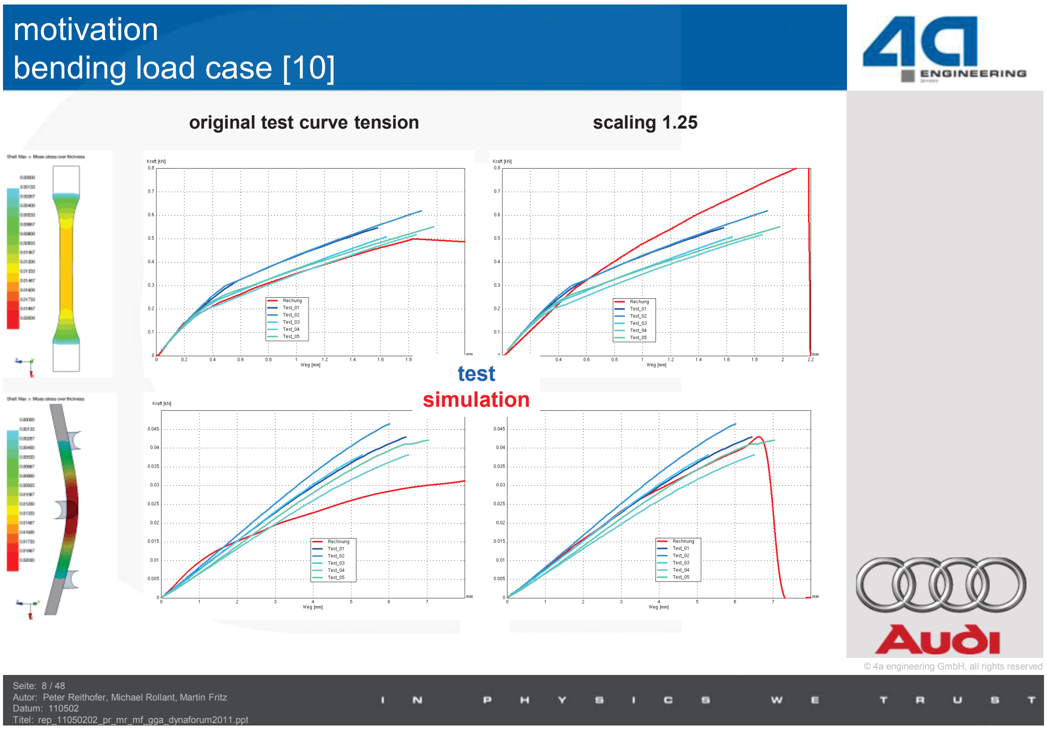
motivation
bending load case [10]
original test curve tension
scaling 1.25
test
simulation
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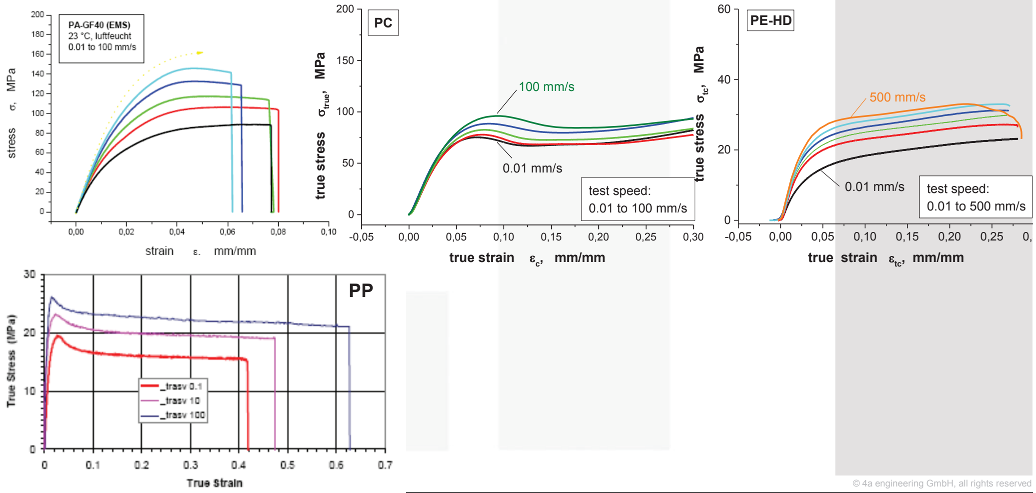
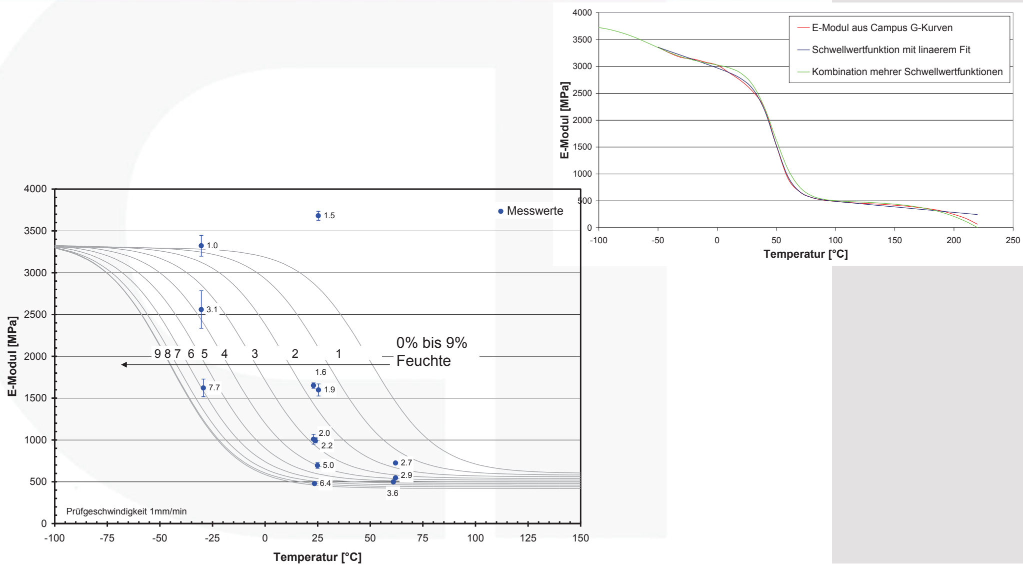
polymer materials
general behavior

Depending on the material type the dynamic behavior is more or less significant, as shown below. [1], [2], [3]

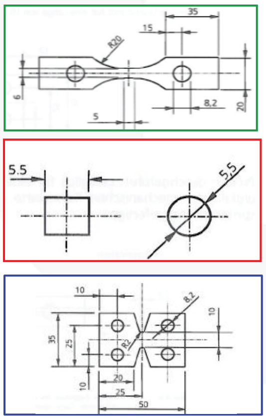


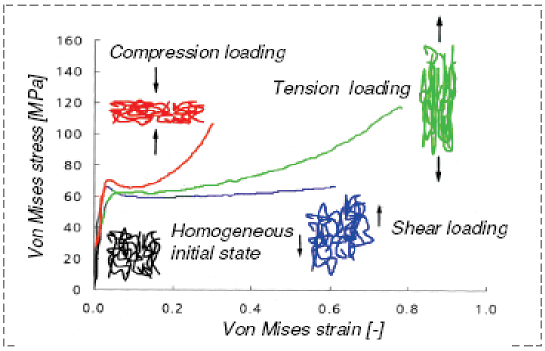
polymer materials
influences



classical approach for measurement of thermoplastics

For the measurement of the mechanical behavior of thermoplastics at high velocities and different loading cases specially prepared specimens and optical measurement equipment are needed. The classical highly complex approach and the huge amount of measurement data have to be handled to get good true stress / strain curves under constant strain rates. [4] [5] [6]



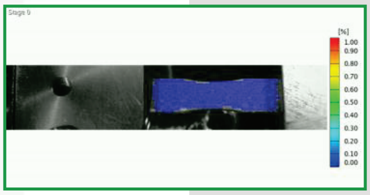


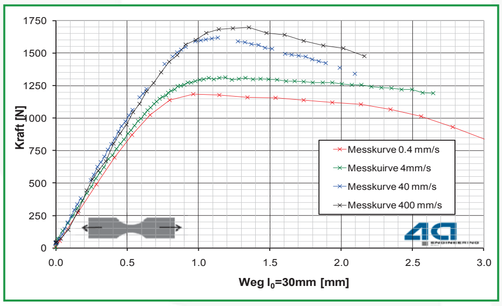
classical approach for measurement of thermoplastics

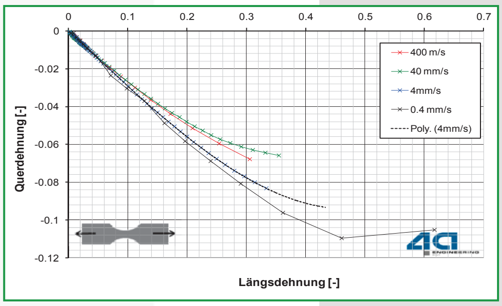
static and dynamic tension tests

For different test velocities the force and traverse displacement is measured. To measure local longitudinal and lateral strains the speckle pattern is optical detected and evaluated by the method of grey scale correlation.

The strain measurement allows to determine local and global deformations and to evaluate true stress strain curves.





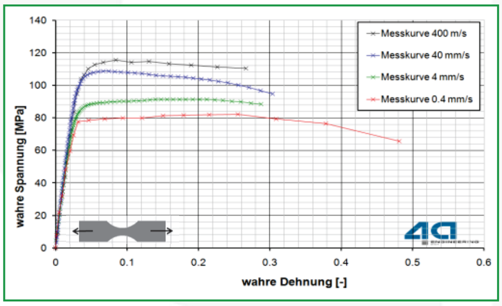


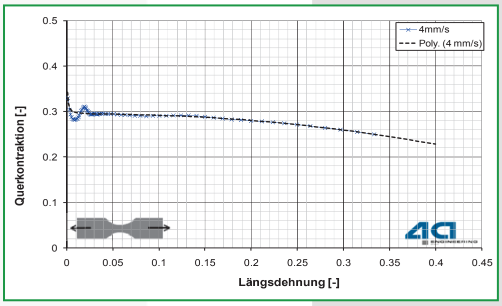
classical approach for measurement of thermoplastics

static and dynamic tension tests

The evaluation of the true stress strain curves is conducted under the assumption that the elongation in the thickness correlates to the laterally measured strain.

The lateral contraction shows a typical well known behavior of polymers. With increasing longitudinal elongation, a volume growth of the material could be measured.





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I N P H Y S I C S W E T R U S T

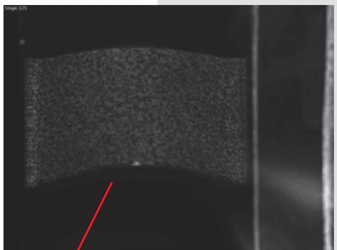
classical approach for measurement of thermoplastics

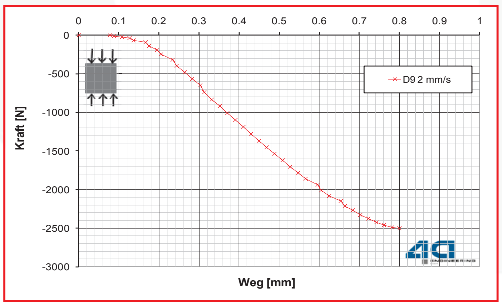
static compression tests

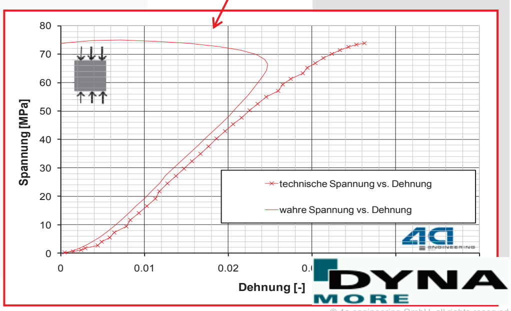
As mentioned before, polymers show different mechanical behavior under compression and tension loading conditions. For that reason the compression tests were conducted.

Due to small sample sizes and the sample geometries, the main difficulty performing compression load cases is, that it is very hard to measure useable stress strain curves.

Most of the time it is not possible to derive a thick enough sample that enables to conduct a test without delivering buckling results as shown in the diagram below.







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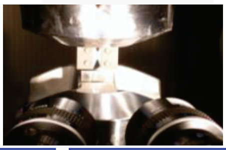
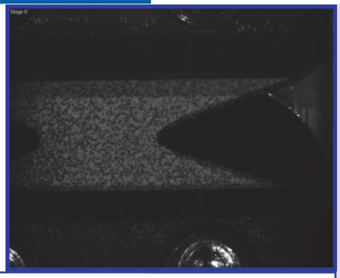
I N P H Y S I C S W E T R U S T

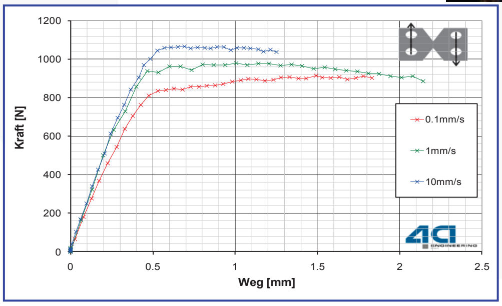
classical approach for measurement of thermoplastics

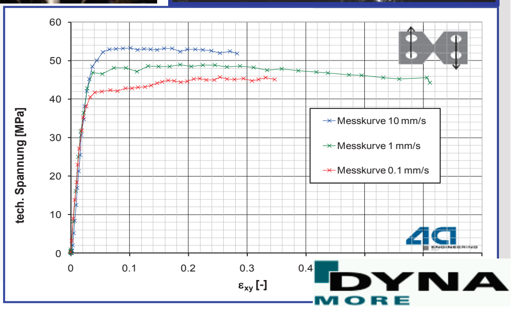
static shear tests

The shear tests were conducted with sample geometries based on the work of Junginger. The shear moduli (~950 MPa) determined out of the tests correlate to shear moduli (975 MPa) determined out of tensile tests.









4a Impetus
general mode of operation

test specimen manufacturing

specimen close to reality
(flat test specimen out of a real manufacturing process)

realistic test conditions
(dynamic bending load, most typical load case)

experiments

cost-effective load without additional actuation
(loaded mass – potential und kinetic energy)

analysis method

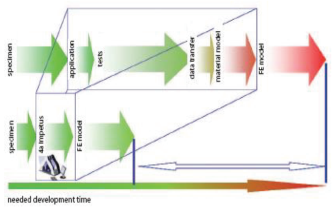
semi analytical evaluation process
(analytical evaluation process plus optional usage of neuronal network for a faster determination of the initial values, optical evaluation process)

solving the complex load situation by integrated simulation process
(explicit simulation)

return of values

output of material data for simulation or direct use
(appropriate format optimal output – test curves – material cards – stochastic outputs)

4a Impetus
dynamic tests up to a velocity of 10 m/s are possible



bending test on 4a Impetus

4a Impetus
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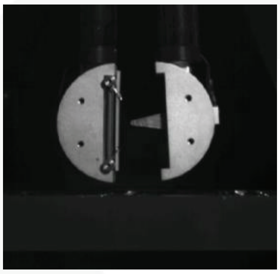
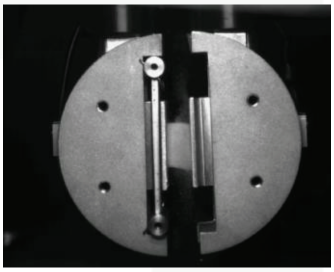
I N P H Y S I C S W E T R U S T

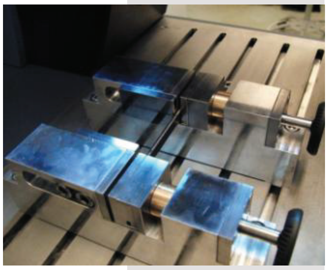
4a Impetus
dynamic tests up to a velocity of 10 m/s are possible



bending test



compression test



fixed 3 Point Bending test

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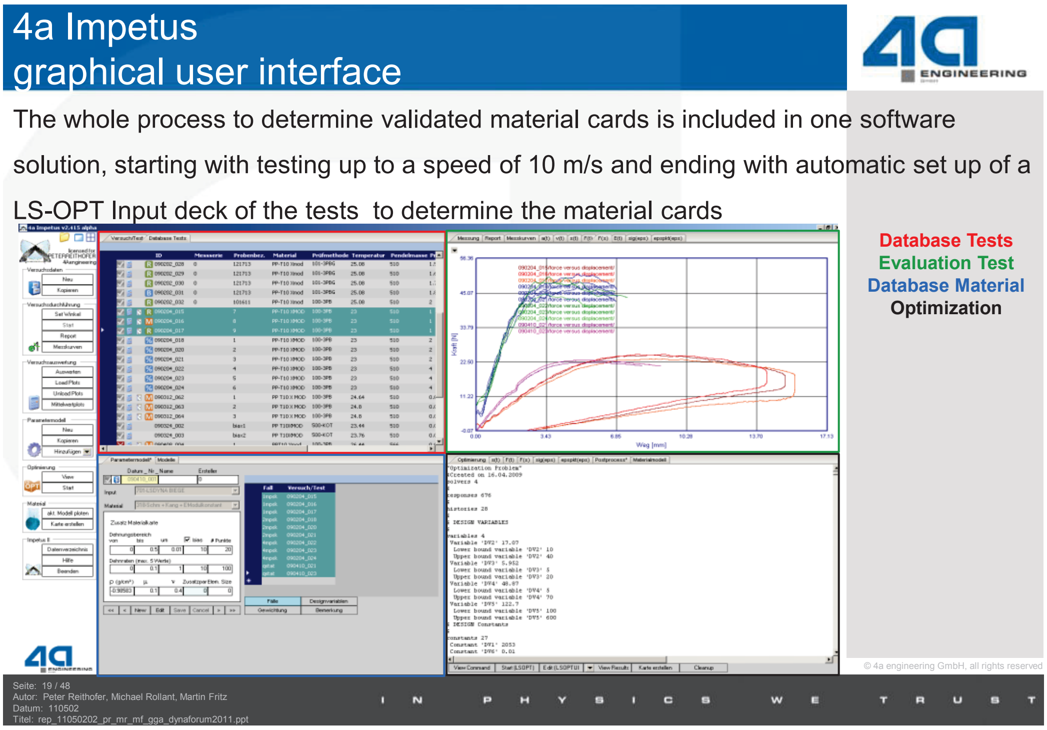
4a Impetus
graphical user interface
The whole process to determine validated material cards is included in one software solution, starting with testing up to a speed of 10 m/s and ending with automatic set up of a LS-OPT Input deck of the tests to determine the material cards
Database Tests
Evaluation Test
Database Material
Optimization
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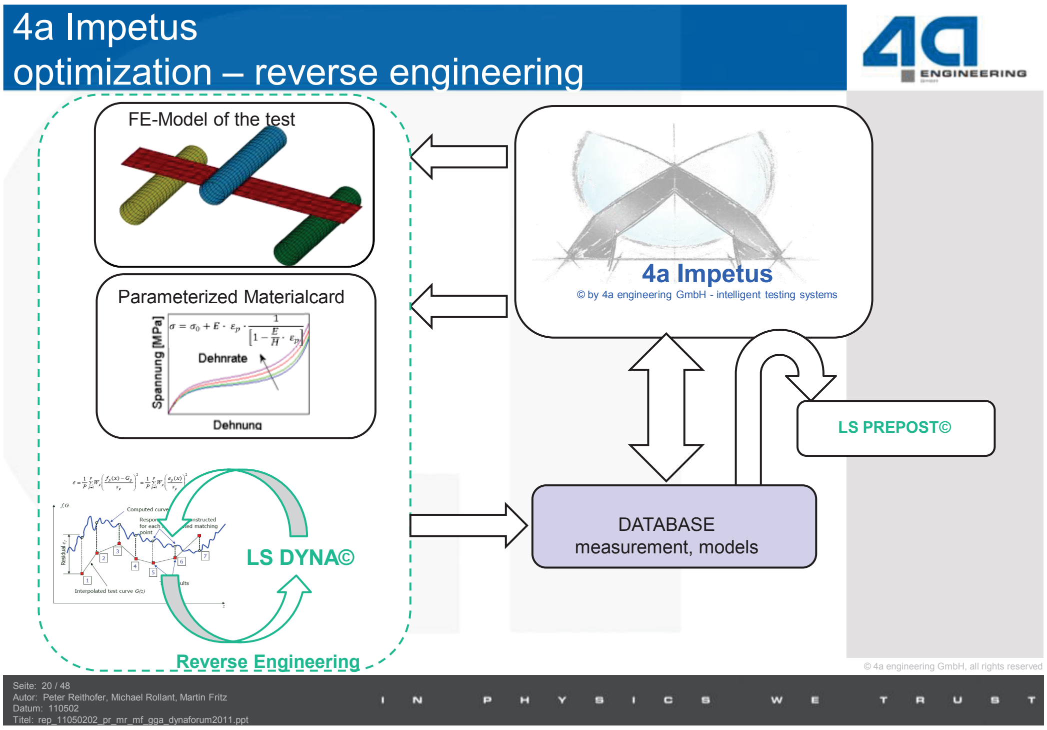
4a Impetus
optimization – reverse engineering
FE-Model of the test
Parameterized Materialcard
Spannung [MPa]
Dehnrate
Dehnung
LS DYNA©
Reverse Engineering
4a Impetus
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LS PREPOST©
DATABASE
measurement, models
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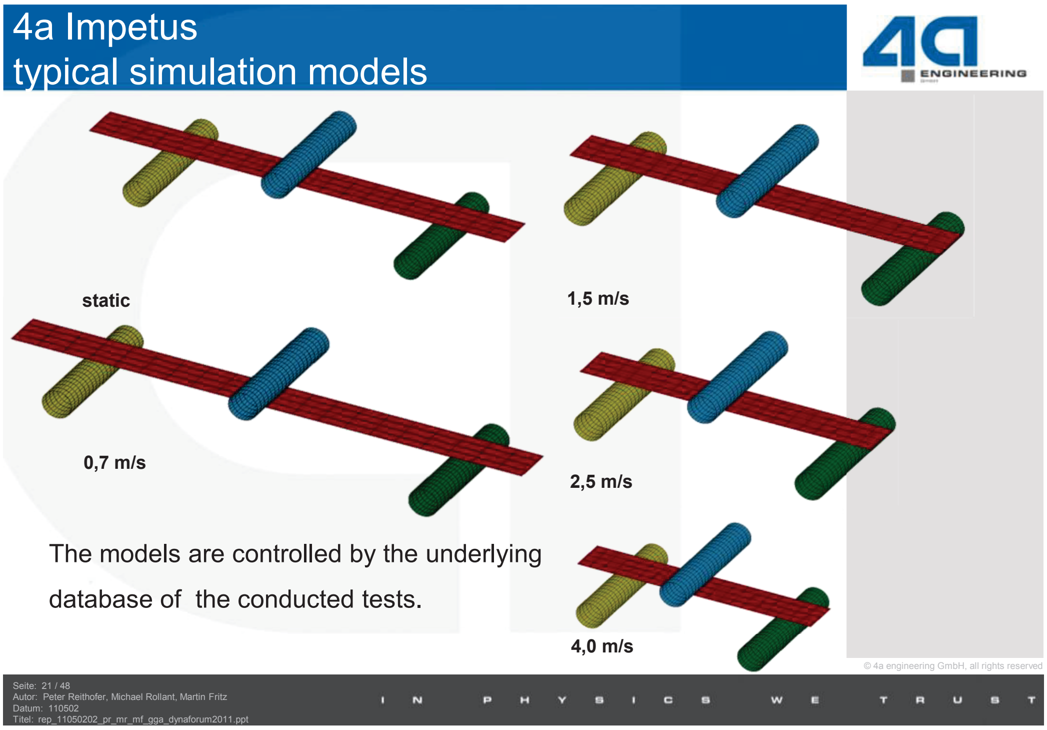
4a Impetus
typical simulation models
ENGINEERING
static
1,5 m/s
0,7 m/s
2,5 m/s
The models are controlled by the underlying database of the conducted tests.
4,0 m/s
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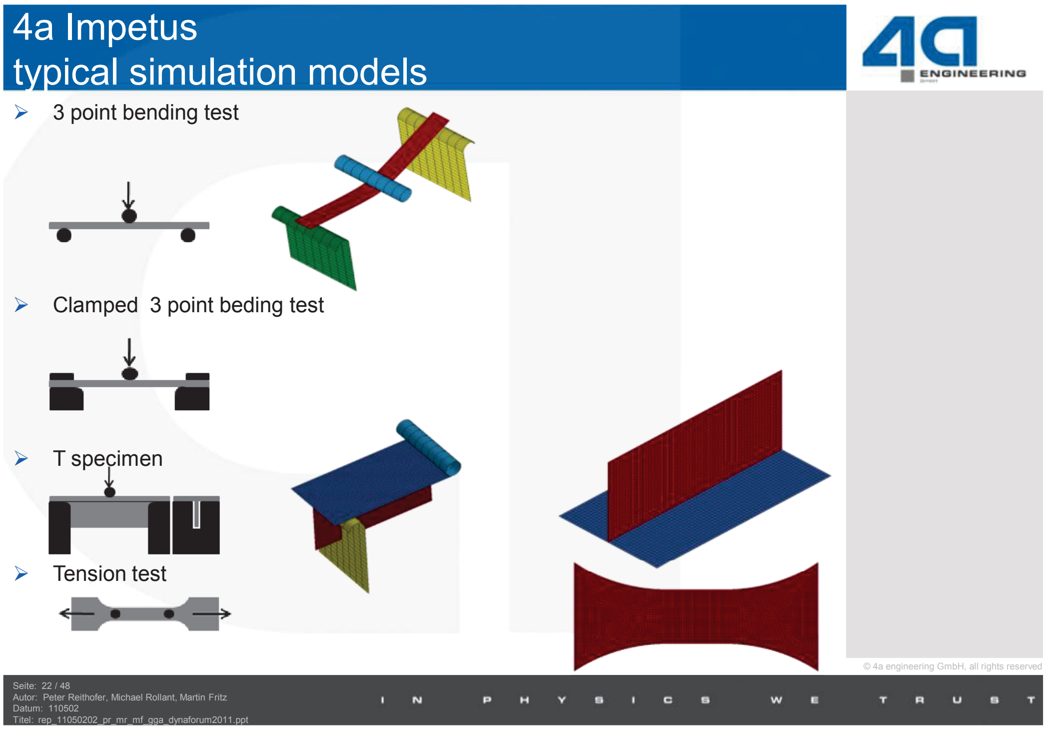
4a Impetus
typical simulation models
ENGINEERING
3 point bending test
Clamped 3 point beding test
T specimen
Tension test
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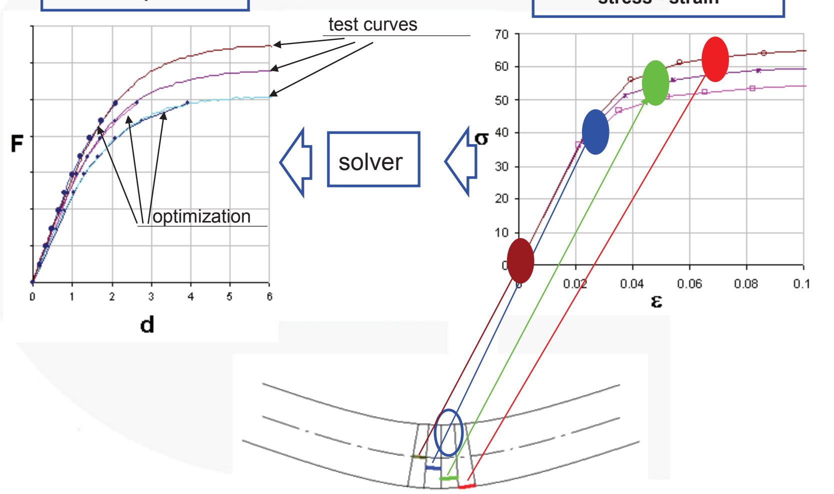
4a Impetus
optimization – reverse engineering

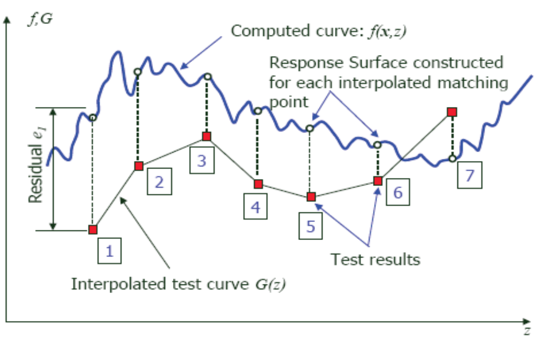


Source: DA Fritz

4a Impetus
optimization – reverse engineering

- minimization of the average deviation between simulation and test curves

$$\varepsilon = \frac{1}{P}\sum_{p=1}^{P} W_p \left(\frac{f_p(x) - G_p}{s_p}\right)^2 = \frac{1}{P}\sum_{p=1}^{P} W_p \left(\frac{e_p(x)}{s_p}\right)^2$$



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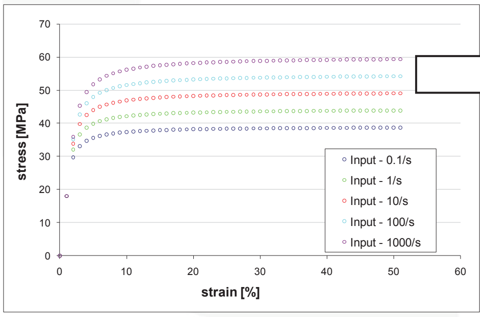
- essential to control the optimization process is a parameterized material card.

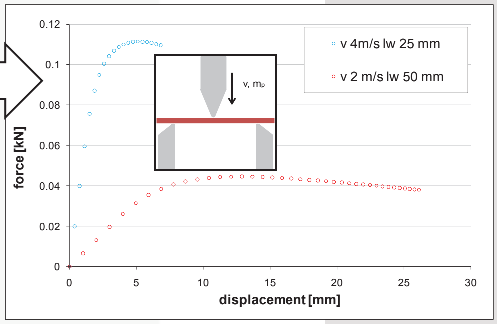
4a Impetus
verification of reverse Engineering

To show if reverse engineering is working a simple mind test was conducted.

- First of all a virtual material was chosen.
- Based on this material simulations of bending tests were done and the force versus displacement was evaluated.
- Finally the reverse engineering for different starting configurations is done and the results are compared.



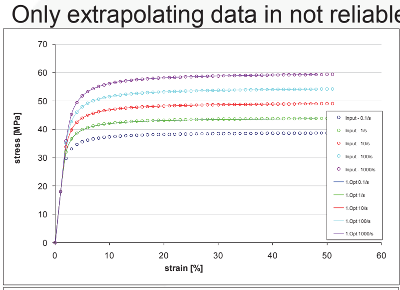
virtual material law

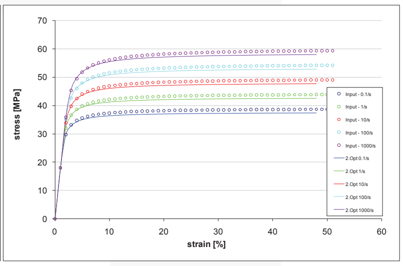


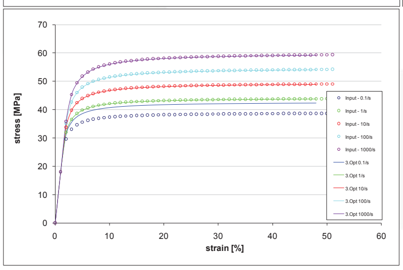
virtual tests

4a Impetus
verification of reverse Engineering

As shown, different starting points of optimization result in the same material behavior.
Only extrapolating data in not reliable area of strain rates lead to different results.







Starting design variables

	Opt 1.	Opt 2.	Opt 3.
1	2000	1000	10000
2	50	100	1
3	25	5	10
4	25	1	50
5	0.1	1	0.001

Final design variables

DV	Input	Opt 1.	Opt 2.	Opt 3.
1	1801	1815	1821	1815
2	22	24.92	22.3	23.99
3	17	19.26	14.34	18.8
4	17	19.14	16.05	18.7
5	0.1	1	0.0651	0.5142

4a Impetus implemented stress strain rules

To reproduce the measured mechanical behavior different material laws can be used to describe the stress strain dependency.

- Bilinear - often implemented in material cards as two parameter law

$$\sigma = \sigma_0 + E_T \cdot \varepsilon_p$$

- Ludwik

$$\sigma = A + B\varepsilon_p^n$$

- Bergström

$$\sigma = A + k\sqrt{1-\exp(-0.5\,\varepsilon_p)}$$

- G'sell Jonas - well known for description of polymers with hardening [7]

$$\sigma = \sigma_0 + K \cdot (1 - e^{-w\cdot\varepsilon_p}) \cdot e^{h\cdot\varepsilon_p^n}$$

- 4a three parameter law (modified Schmachtenberg) [7]

$$\sigma = \sigma_0 + E \cdot \varepsilon_p \cdot \frac{1}{\left[1 - \frac{E}{H} \cdot \varepsilon_p\right]}$$

4a Impetus implemented strain rate rules

Different well known strain rate rules are available in 4a Impetus

- Power law – simplest law

$$\sigma = \sigma_0(\varepsilon)\,\dot{\varepsilon}^n$$

- Cowper Symonds – often implemented

$$\sigma = \sigma_0(\varepsilon)\left[1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}}\right]$$

- Johnson Cook – especially for high strain rates

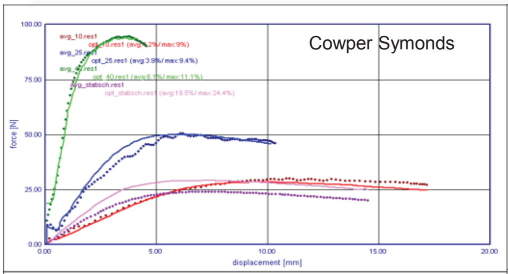
$$\sigma = \sigma_0(\varepsilon)\left[1 + C\,\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]$$

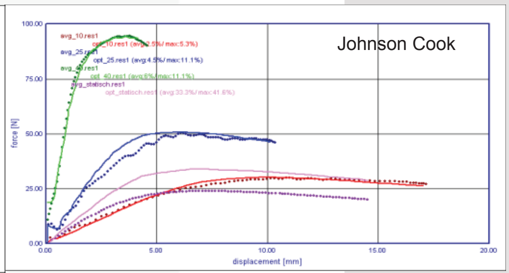
- Kang – can also rebuild low strain rates

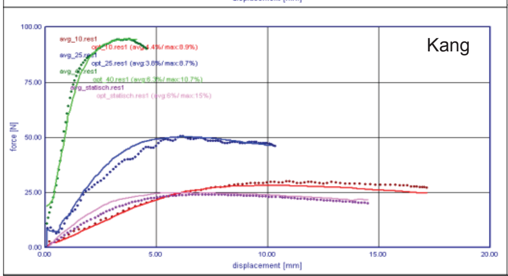
$$\sigma = \sigma_0(\varepsilon)\left[1 + C_1\,\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + C_2\,(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0})^2\right]$$

4a Impetus
implemented strain rate rules

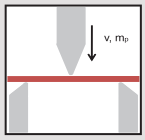
Best representation of velocity dependent measurement through Kang model







v m/s	l_w mm	m pendulum g
4	25	510
2.5	40	510
1	60	1300
0.001	50	



···· averaged test curves
— result of simulation

4a Impetus
implemented LS DYNA Material Cards

Currently the following LS DYNA material cards are implemented in the 4a Impetus system. Further material cards can be easily integrated in the material card build up process.

- Mat 24 (MAT_PIECEWISE_LINEAR_PLASTICITY)
  very fast material card. Combined with dynamic bending test this material card is a possibility to take into account an average tension/ compression behavior.
  Can be also used with LS DYNA implicit.

- Mat 81 (MAT_PLASTICITY_WITH_DAMAGE)
  like Mat 24 with the enhancement of damage model

- Mat 124 (MAT_PLASTICITY_COMPRESSION_TENSION)
  possibility to consider different Tension and Compression loading
  Only available for LS-DYNA explicit.

- Mat 187 (MAT_SAMP-1) [8][9]
  recent development especially for polymers,
  treat different loading cases, multi axiality and damage.
  Only available for LS-DYNA explicit. At the moment not all features are implemented in 4a Impetus.

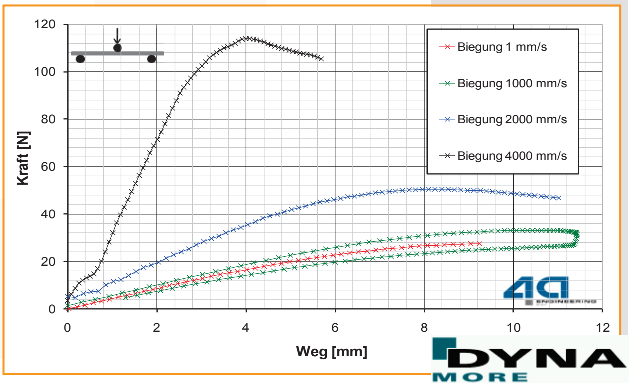
4a Impetus

test results – three point bending test (static and dynamic)

The quasi static tests are conducted on a constant test velocity of 1mm/s. The impact velocity of the dynamic tests and the gauge length are varied. Due to this variation a strain rate range of 0.01 to 200 1/s could be covered in the whole test program.

It has to be mentioned that in the case of three point bending test the material behavior could be similarly examined under tension and compression load cases.

Further more in the dynamic test it is also possible to measure the unloading case.

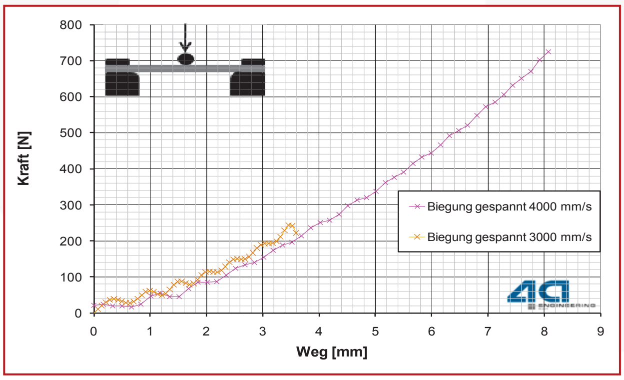


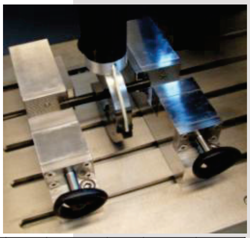
v_0 [mm/s]	l_w [mm]	$m_{Pendular}$ [g]	b [mm]	t [mm]	l [mm]
4000	24	510	6	1.95	35
2000	30	510	6	1.95	40
1000	50	510	6	1.95	60
1	50		6	1.95	60

4a Impetus

test results – fixed bending test (dynamic)

Complex material models are often based on a general flow surfaces. Together with the method of reverse engineering, bending tests cannot dissolve the difference between tension and compression. Combined with a fixed bending test, which is mainly dominated by tension loading, material cards could be determined with respect to different mechanical behavior.



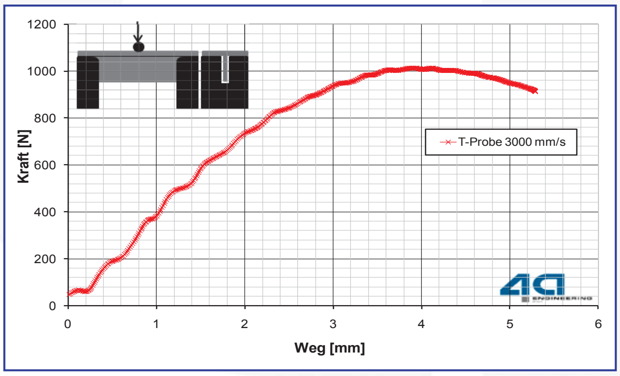


v_0 [mm/s]	l_w [mm]	$m_{Pendular}$ [g]	b [mm]	t [mm]	l [mm]
3000	50	2107	6	1.95	155
4000	50	2107	6	1.95	155

4a Impetus

test results – fixed bending test (dynamic)

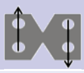
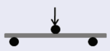
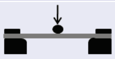
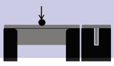
For further validations simple component tests were conducted. A typical geometrical engineering part is a stiffening rib. In the bending load case we will find a compression zone as well as a tension zone with high strain. Due to this loading situation this simple part is a good base for final the validation of material cards.



v_0 [mm/s]	l_w [mm]	$m_{Pendular}$ [g]	b_{Gurt} [mm]	t_{Gurt} [mm]	h_{Steg} [mm]	t_{Steg} [mm]	l [mm]
3000	50	1311	17	1.89	12	1.56	60

Material Card Generation

typical ways

	*MAT_24 Dynamat	*MAT_187 Dynamat	*MAT_24 Impetus	*MAT_124 Impetus	*MAT_124 Impetus
	**base**	**base**	validation	validation	validation
		**base**			
	validation	**base**	validation	validation	validation
	validation	validation	**base**	**base**	**base**
				**base**	
	validation	validation	Validation	validation	**base**
	validation	validation	validation	validation	validation

classical approach

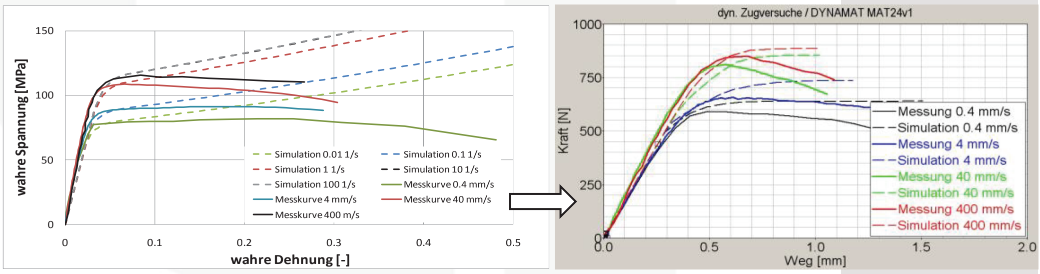
4a Impetus

Materialcard Mat24 (picewise_linear_plasticity) v1

material card generation based directly on measured stress strain curves

Classical approach:

- True stress / strain curves are determined on assumption of incompressibility. The assumption correlates with the used material law, not taking into account the typical polymer behaviour of volume increase during loading.
- Measurement results are used until end of on uniform elongation, thereafter the true stress strain curves are extrapolated exponentially.



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Datum: 110502
Titel: rep_11050202_pr_mr_mf_gga_dynaforum2011.ppt

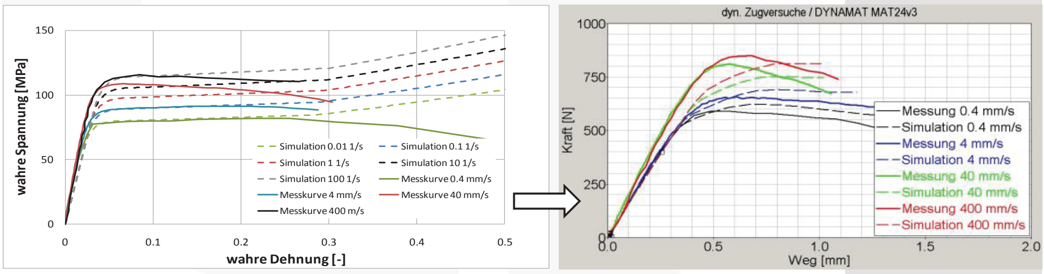
I N P H Y S I C S W E T R U S T

Materialcard Mat24 (picewise_linear_plasticity) v3

material card generation iterative adjustment of stress / strain curves

iterative procedure:

- Based on prior directly generated material cards an iterative procedure is used to find a best fit of the virtual tensile test according to real measurement. This work is often done by engineering judgment.
- The idealization of the tensile bar is an important factor to predict the necking. Due to the aspect of necking, mostly a small element size has to be used. This small element size does not correlate to the use mesh sizes in typical crash simulations.



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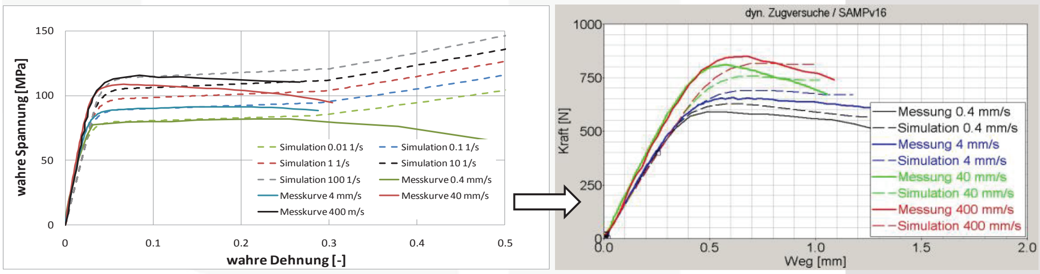
I N P H Y S I C S W E T R U S T

Materialcard SAMP-1 v15

iterative procedure:

- The effort for generating a material card increases significantly. A fitting for the load cases tension, compression and shear has to be done, to get the final material card. The idealization of the virtual tests has also to be considered.
- The material model will also expect isochoric determined stress strain curves, even if the lateral strain is considered correctly.



Materialcard Impetus *MAT_24

material card generation – using automated standardized process

- Bilinear

$$\sigma = \sigma_0 + E_T \cdot \varepsilon_p$$

- G'sell Jonas

$$\sigma = \sigma_0 + K \cdot (1 - e^{-w \cdot \varepsilon_p}) \cdot e^{h \cdot \varepsilon_p^n}$$

- 4a three parameter law (modified Schmachtenberg)

$$\sigma = \sigma_0 + E \cdot \varepsilon_p \cdot \frac{1}{\left[1 - \frac{E}{H} \cdot \varepsilon_p\right]}$$

- Cowper Symonds

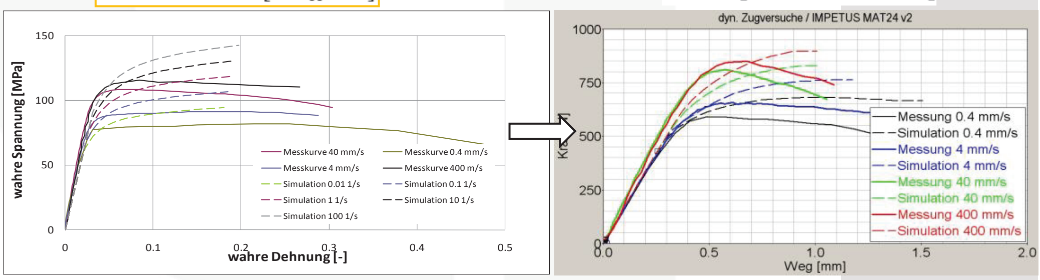
$$\sigma = \sigma_0(\varepsilon)\left[1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{p}}\right]$$

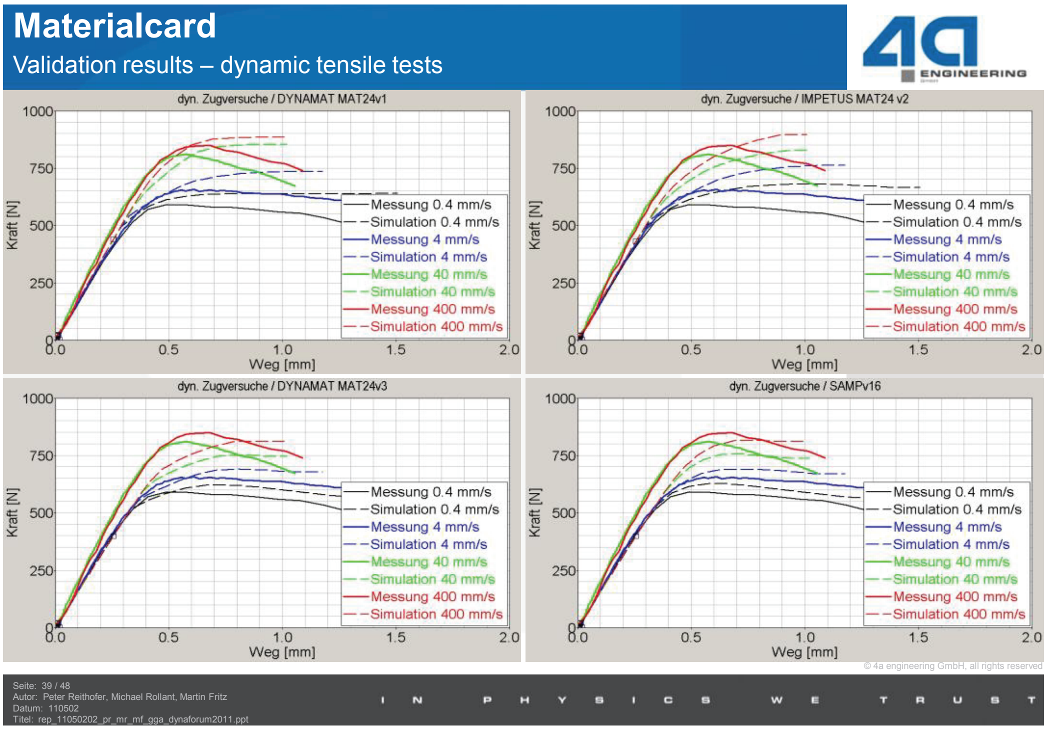
- Johnson Cook

$$\sigma = \sigma_0(\varepsilon)\left[1 + C \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right]$$

- Kang

$$\sigma = \sigma_0(\varepsilon)\left[1 + C_1 \ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} + C_2 \left(\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^2\right]$$




Materialcard
Validation results – dynamic tensile tests
ENGINEERING
dyn. Zugversuche / DYNAMAT MAT24v1
dyn. Zugversuche / IMPETUS MAT24 v2
dyn. Zugversuche / DYNAMAT MAT24v3
dyn. Zugversuche / SAMPv16
Kraft [N]
Weg [mm]
Messung 0.4 mm/s
Simulation 0.4 mm/s
Messung 4 mm/s
Simulation 4 mm/s
Messung 40 mm/s
Simulation 40 mm/s
Messung 400 mm/s
Simulation 400 mm/s
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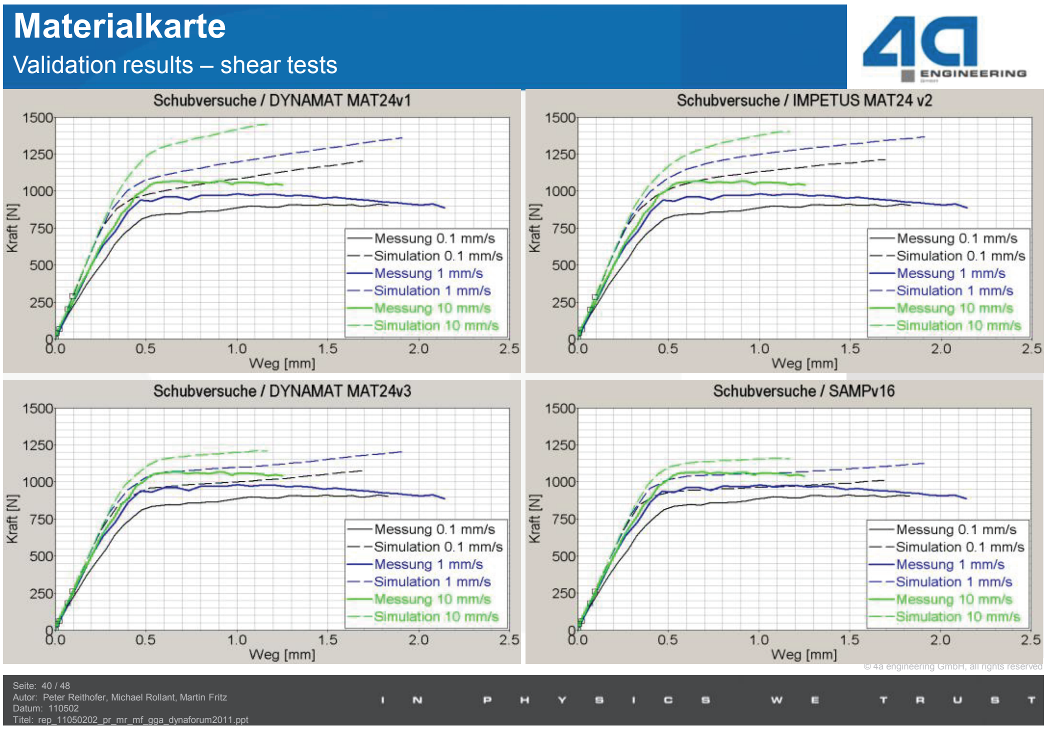
Materialkarte
Validation results – shear tests
ENGINEERING
Schubversuche / DYNAMAT MAT24v1
Schubversuche / IMPETUS MAT24 v2
Schubversuche / DYNAMAT MAT24v3
Schubversuche / SAMPv16
Kraft [N]
Weg [mm]
Messung 0.1 mm/s
Simulation 0.1 mm/s
Messung 1 mm/s
Simulation 1 mm/s
Messung 10 mm/s
Simulation 10 mm/s
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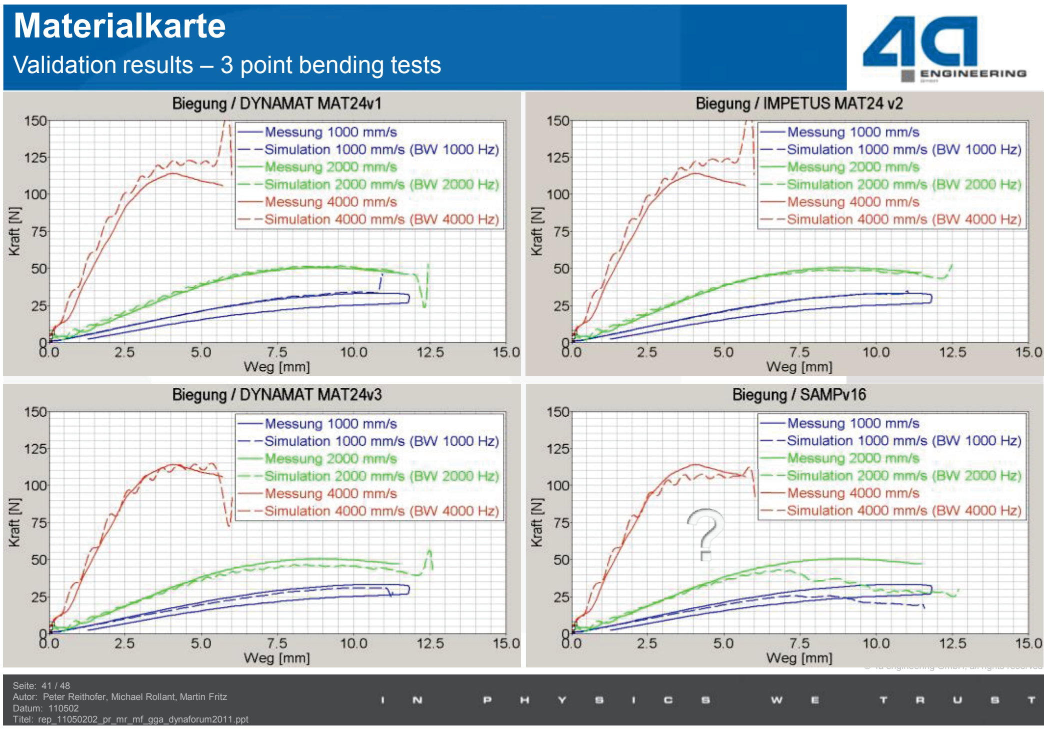
Materialkarte
Validation results – 3 point bending tests
4a ENGINEERING
Biegung / DYNAMAT MAT24v1
Biegung / IMPETUS MAT24 v2
Biegung / DYNAMAT MAT24v3
Biegung / SAMPv16
Messung 1000 mm/s
Simulation 1000 mm/s (BW 1000 Hz)
Messung 2000 mm/s
Simulation 2000 mm/s (BW 2000 Hz)
Messung 4000 mm/s
Simulation 4000 mm/s (BW 4000 Hz)
Kraft [N]
Weg [mm]
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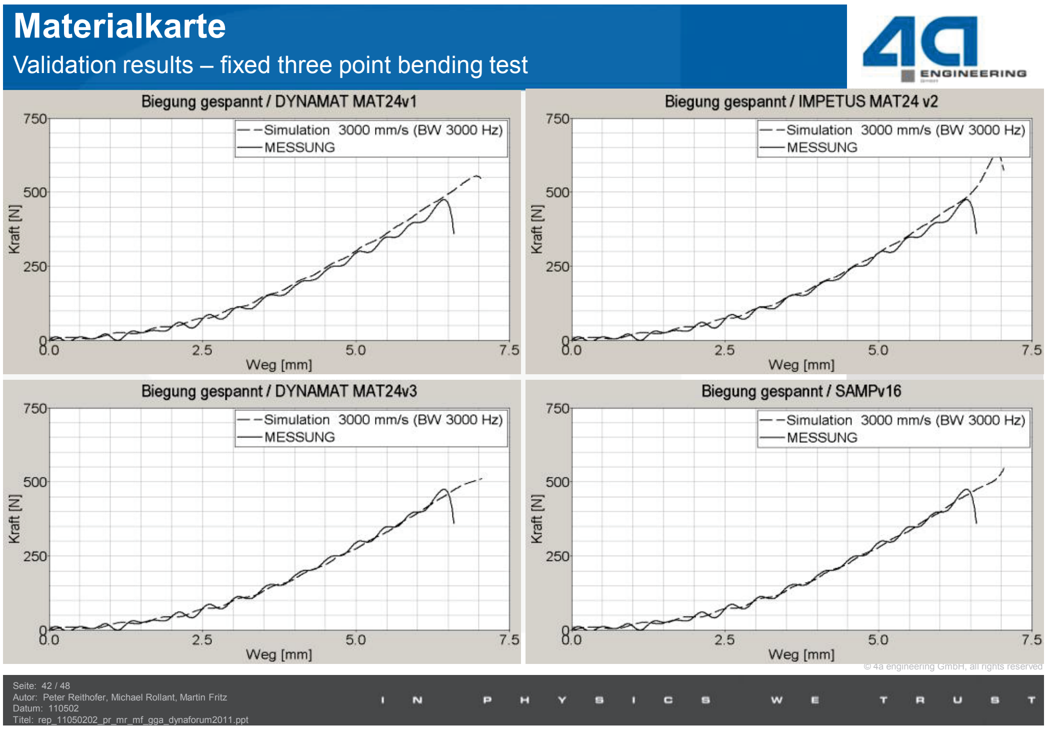
Materialkarte
Validation results – fixed three point bending test
4a ENGINEERING
Biegung gespannt / DYNAMAT MAT24v1
Biegung gespannt / IMPETUS MAT24 v2
Biegung gespannt / DYNAMAT MAT24v3
Biegung gespannt / SAMPv16
Simulation 3000 mm/s (BW 3000 Hz)
MESSUNG
Kraft [N]
Weg [mm]
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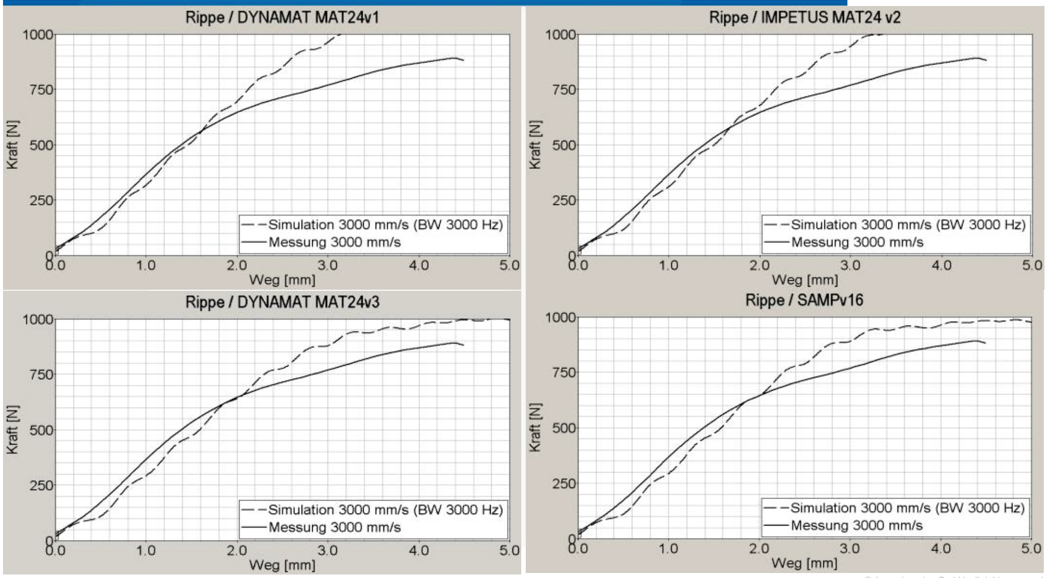
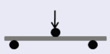
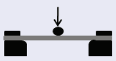
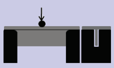
Materialkarte

Validation results – component test rip



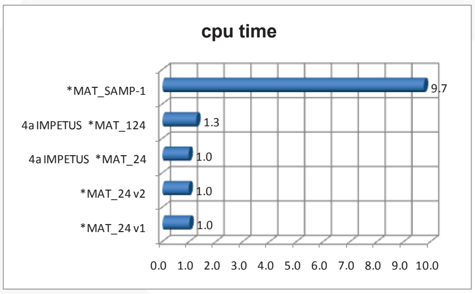
Material Card Generation

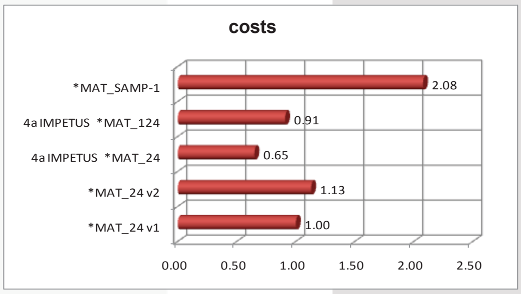
Validation results

	*MAT_24 Dynamat v1	*MAT_24 Dynamat v3	*MAT_187 Dynamat	*MAT_24 Impetus
	-	+	++	~
				
	-	~	~	-
	+	++	?	++
				
	~	+	++	+
	-	~	~	~

Material Card Generation

CPU – Time vs. costs

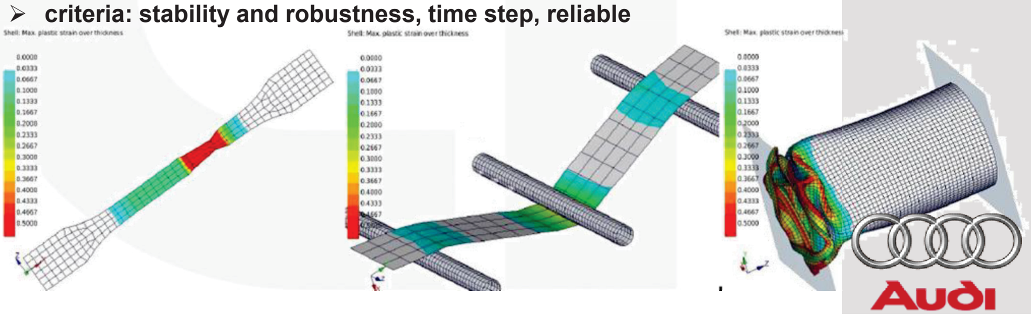




QM Tool

validation of material cards [10]

- **fast evaluation of material cards**
- **simple mind models**
  - tension
  - bending
  - crushing tube - „overload“
  - rotating Square
- **criteria: stability and robustness, time step, reliable**



conclusion

4a impetus builds up an efficient and reliable process, starting with realistic tests and finally ending up with a validated material card. Recent developments of new test methods for 4a Impetus have been presented, that satisfy the needs of complex material models as well as the expectations with regard to easy and favorable testing.

4a impetus offers

- **extensive test opportunities**
- **database links all tests to the evaluated material cards**
- **life measurement and optimization → validated material cards**

appendix literature

[1] **Werkstoffprüfung der Kunststoffe - V**
R. W. Lang, Vorlesungsbehelf IWKP 2002

[2] **Characterization of Dynamic Behavior of Engineering Polymers**
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[3] **Material data for CAE simulation. The approach of Basell Polyolefins**
M. Nutini, 4a –VDI Technologietag 2008

[4] **Mechanik der Kunststoffe**
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M. Nutini, M. Vitali, 7th GERMAN LS-DYNA Forum, Bamberg 2008

[7] **Anwendung von neuronalen Netzen für die Materialdatengener-ierung am Beispiel von Polyamid**
P. Fuchs, Institut für Werkstoffkunde und Prüfung der Kunststoffe an der Montanuniversität Leoben

[8] **Validation and Verification of Plastics under Multiaxial Loading**
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[9] **A Constitutive Formulation for Polymers Subjected to High Strain Rates**
S. Kolling, A. Haufe, M. Feucht, P. Du Bois 9th International LS-DYNA User Conference

[10] **Kunststoffmaterialien in der Funktionsauslegung bei der Audi AG**
Richard Luijkx, 4a Technologietag 2010