Workshop „Dynamic Plastic Material Characterization using the 4a impetus Pendulum“, Würzburg
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- Measurement technique
- Software
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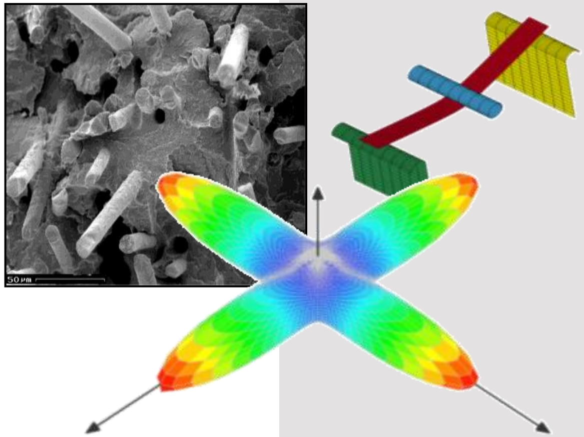
4a engineering GmbH

- 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

4a engineering GmbH

- polymer and materials science
- numerical simulation methods
- fiber reinforced plastics and composites
- method and software development



- case studies product development:

Alpine touring ski binding

LH_2 – tank mounting

RTM – CFK – strut bar

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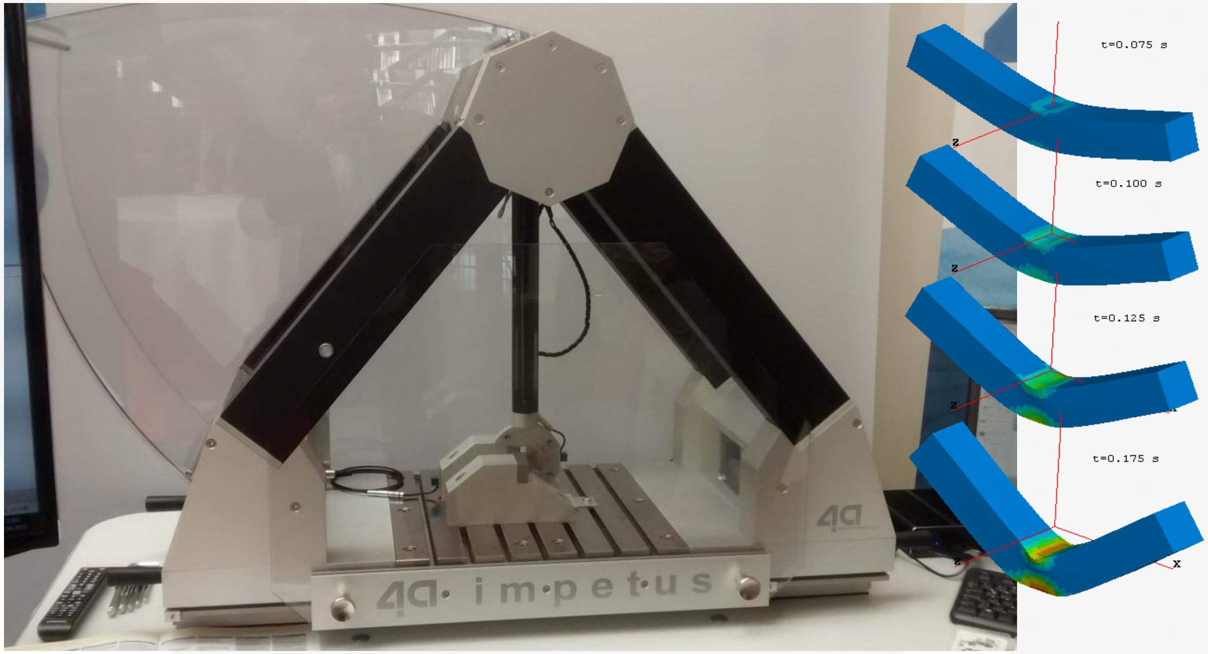
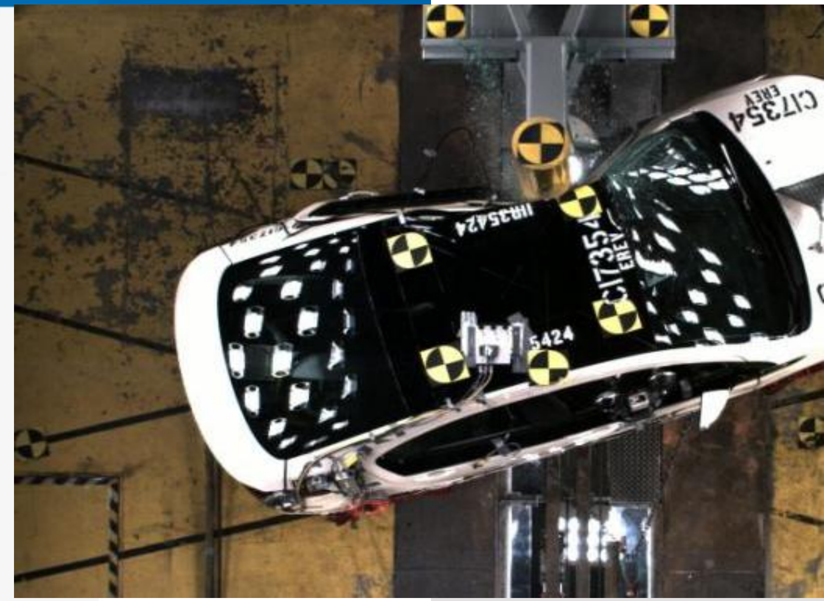
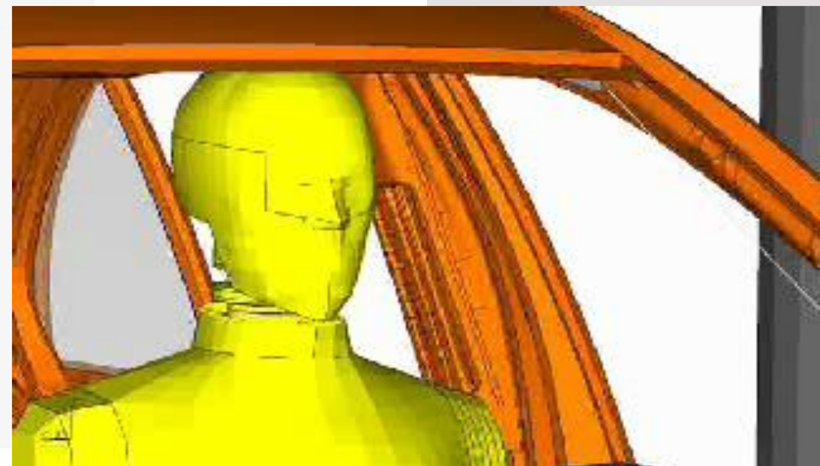
- efficient high-dynamic testing
- crash-behaviour of plastics
- material data for simulation

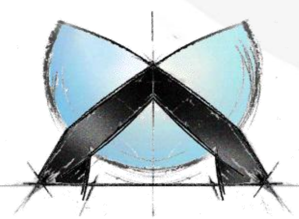




source: http://gm-volt.com/



source: Dynamore GmbH



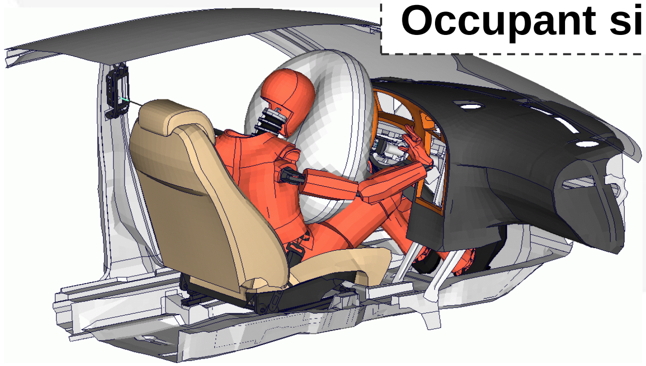
4a impetus - intelligent testing systems
powered by 4a engineering GmbH

Motivation

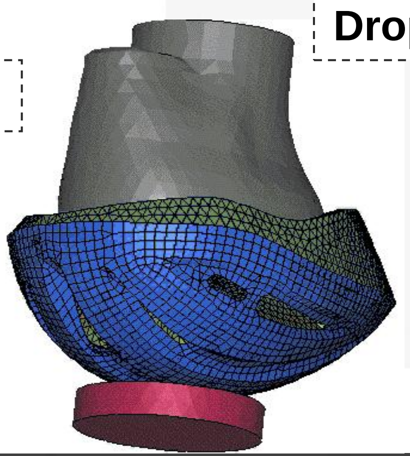
- Motivation: **material card** for simulation of **plastic materials**
  - Under dynamic loading
  - Realistic loading, near to reality
  - Reproducible (database structure)
  - Reduction of development time and costs
  - Evaluation and validation in one system
- Typical applications / simulation topics
  - Automotive industries → occupant and pedestrian safety
  - Drop test → consumer goods

bending test on 4a impetus

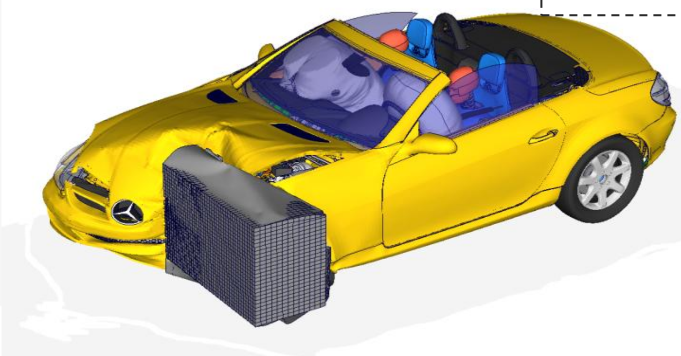
Occupant simulation



Drop test



Crash



Motivation
Industrial needs

Customer wishes:

- Cost reduction → specimen quantity and cost
- Time reduction
- Less testing
- Replacement of tests through simulation

Time to market

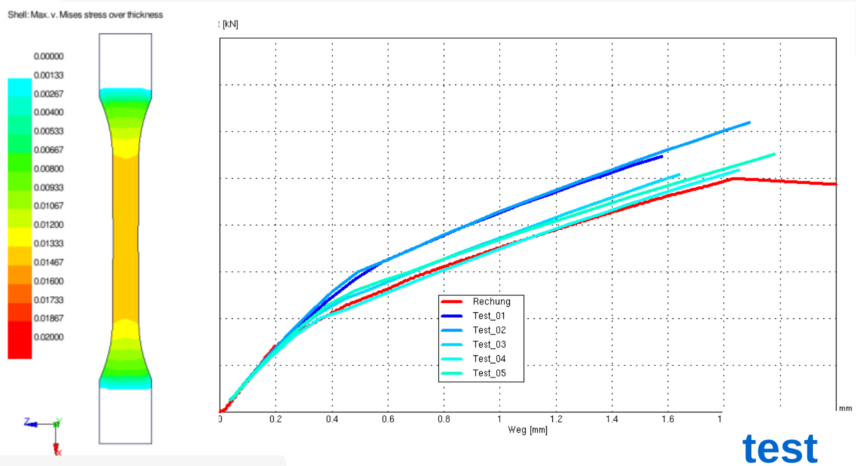
Results in:

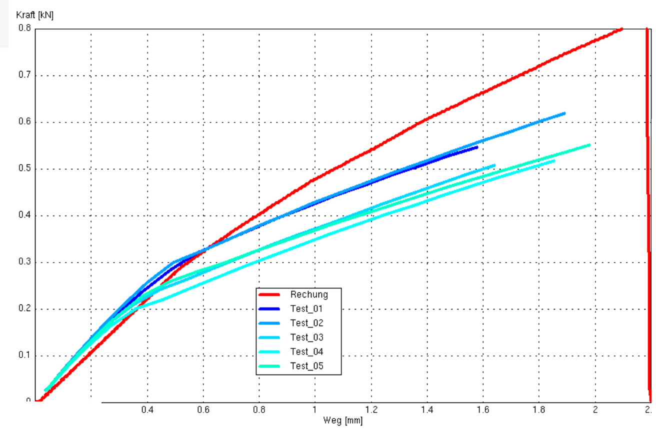
- High reliability of simulation models
- Reliable material cards → more testing
- Smarter test equipment

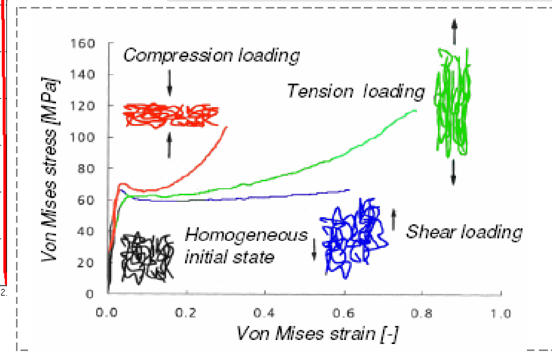
Motivation

Bending load case (loading near to reality)

original test curve tension **scaling 1.25**

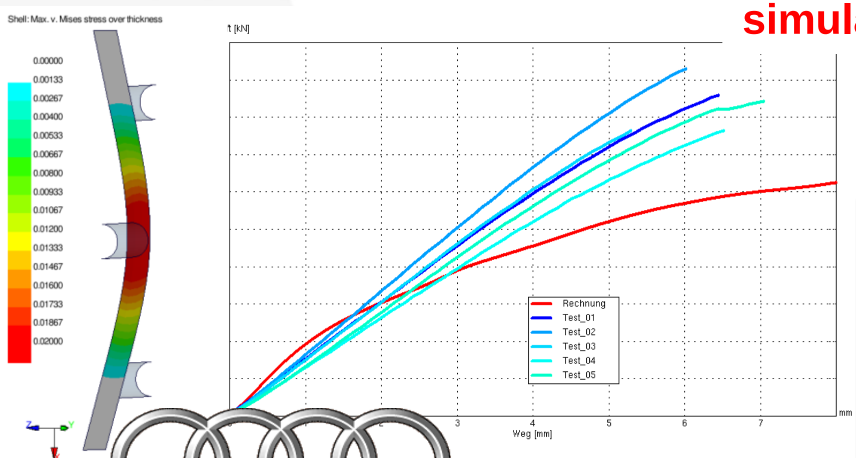


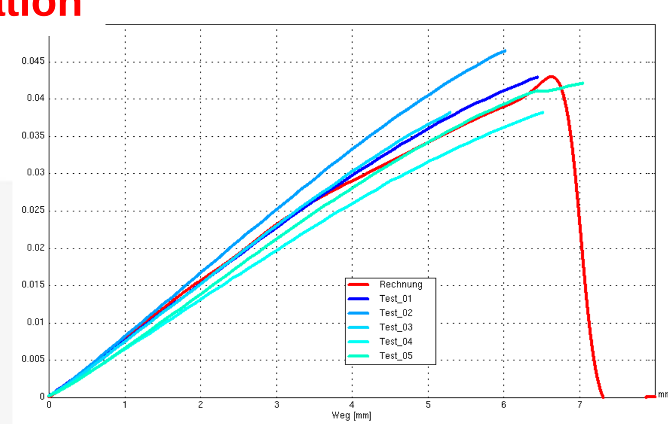




test

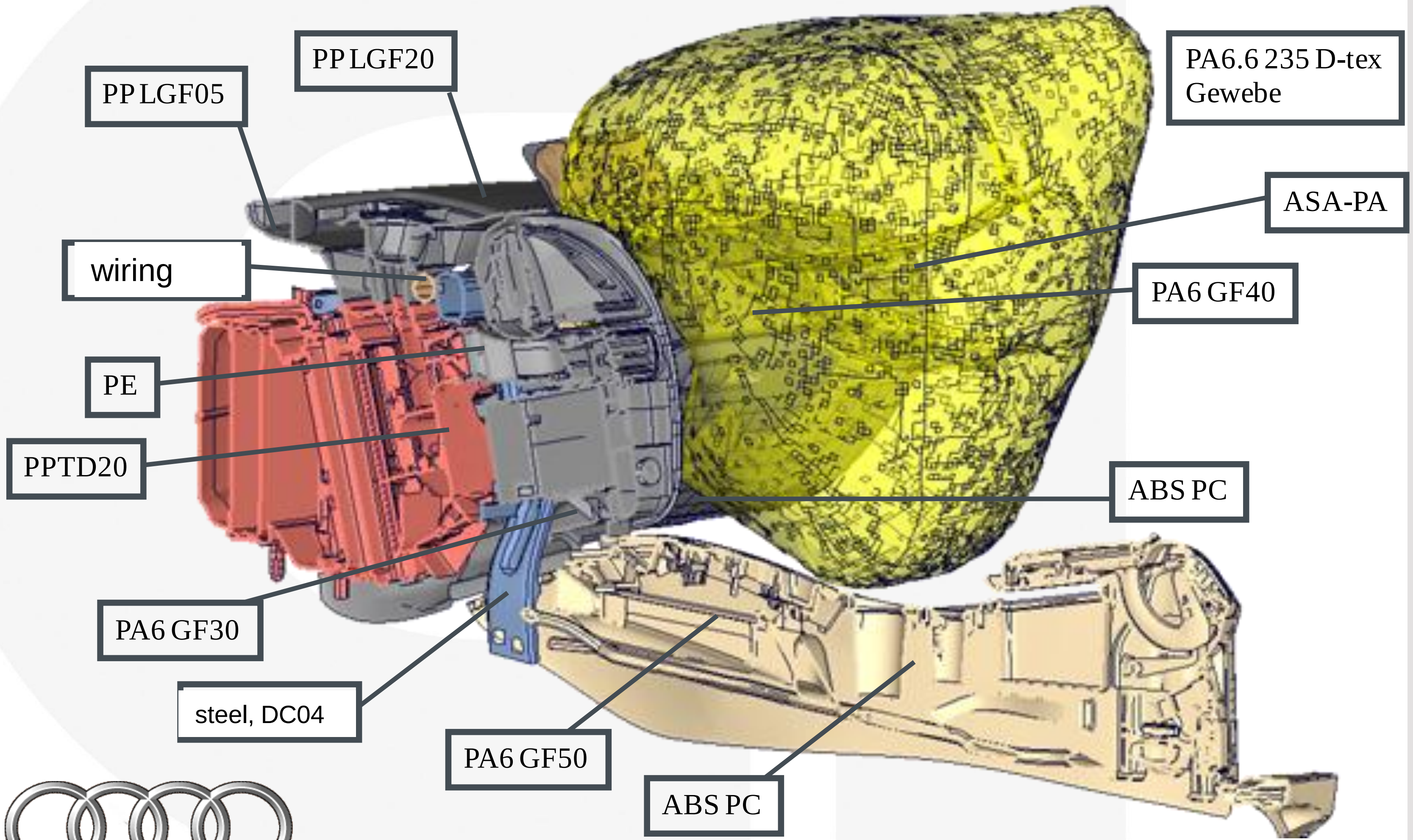
simulation





Many plastics show a strong load type dependency. [1] [2]

Motivation
Material variety (reproducible → database structure)



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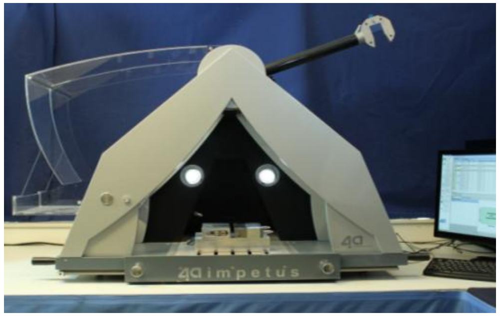
History of 4a impetus

2015

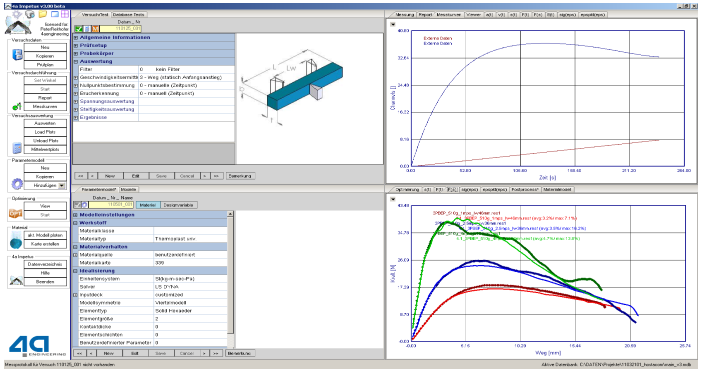
4a impetus
Software solution from the test to the material card

4a impetus Hardware



directly linked

4a impetus Software



External Testing

gom Optical Measuring Techniques

Zwick / Roell

MTS®

INSTRON®

SHIMADZU

ASCII DATA

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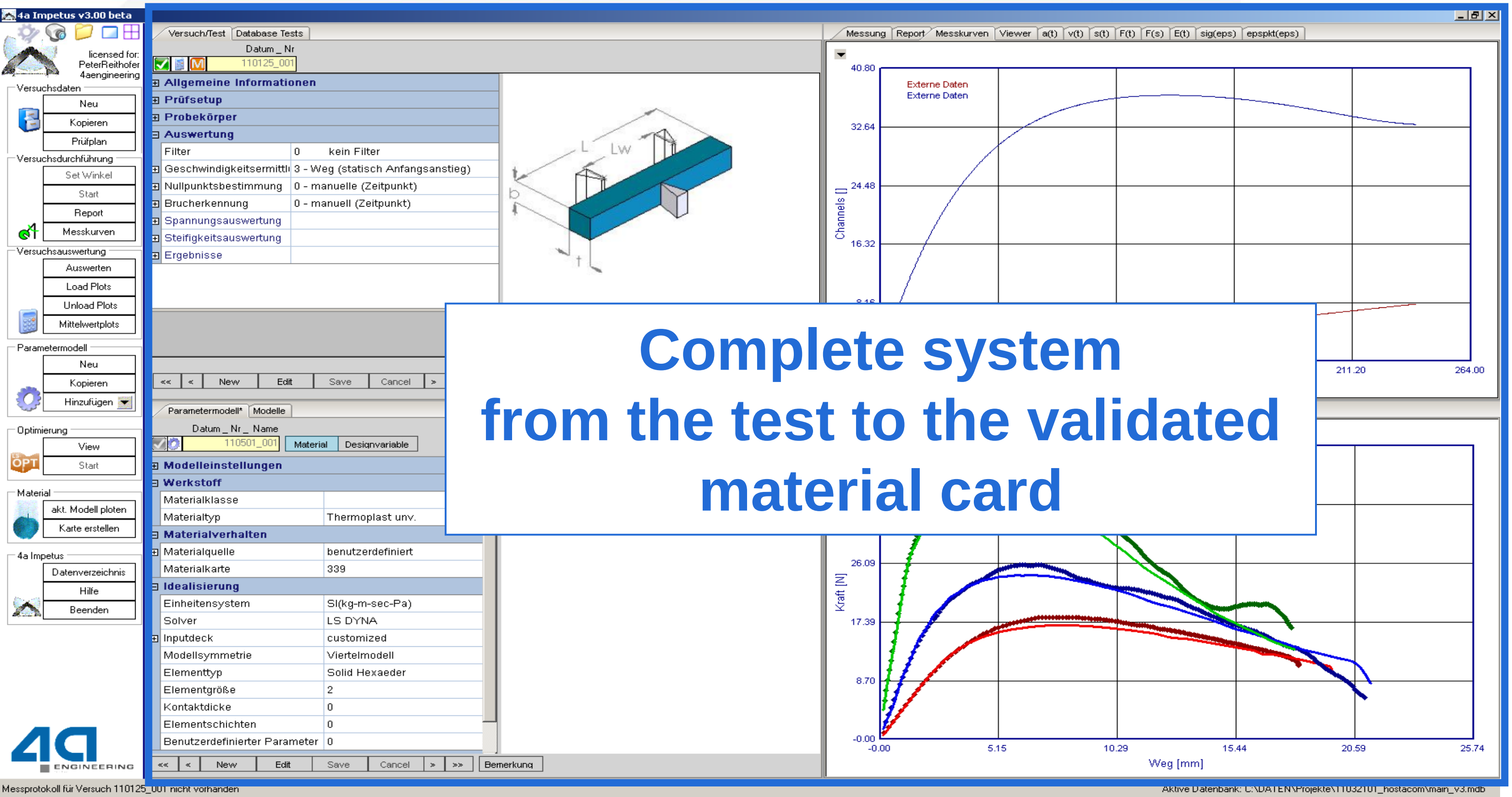
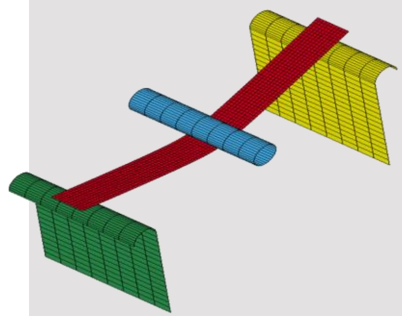
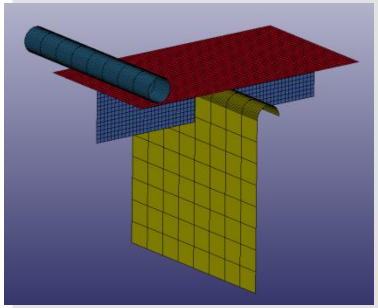
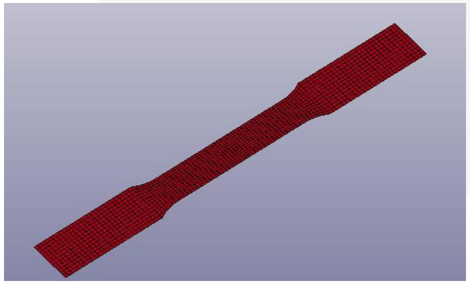
Software solution from the test to the material card

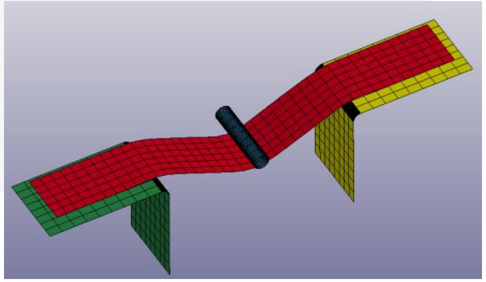


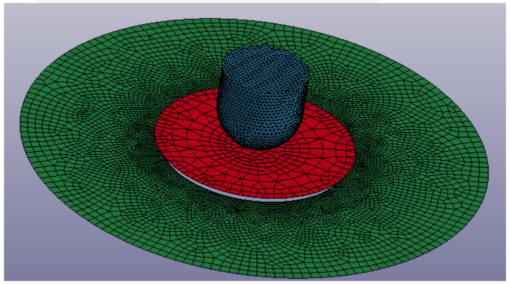
Complete system from the test to the validated material card

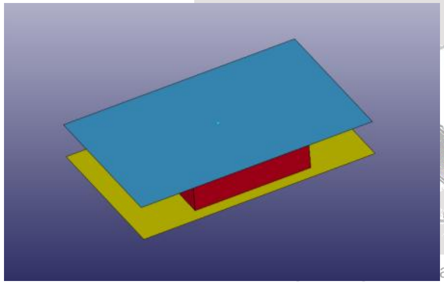












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Applications

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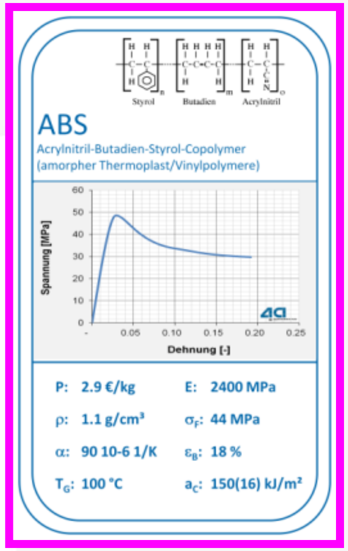
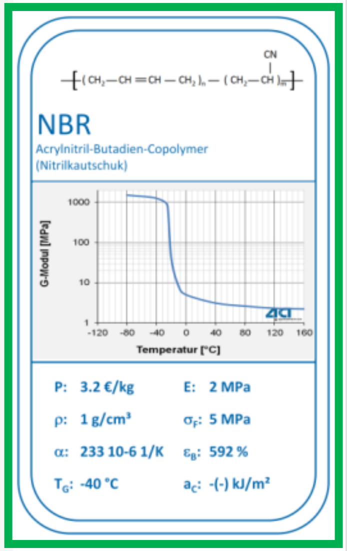
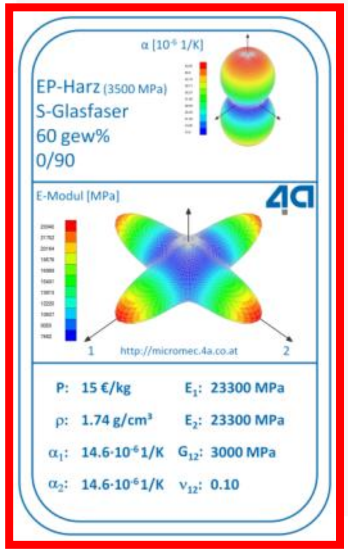
Tested materials

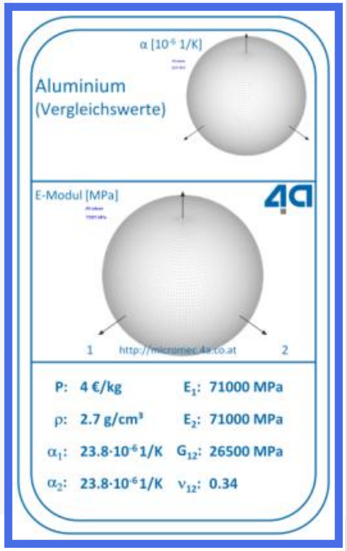
- We have already tested a wide range of
  - thermoplastics (ASA, ABS+PA; ABS+PC; PA6; PA6(6) GF30..50; PA66+P6; PBT GF30; PC; PE; PP; PP+ varnish; PP rubber modified; PP GF20..40; PP Impact modified; PP MX10; PP MX20; PP MX40; PP CF; PP+EPDM; MuCell-materials, …)
  - foams (EPP30..80; PU RG 55, PU RG 65)
  - rubbers (EPDM, SILIKON)
  - thermoset materials (CFK, GFK with epoxy resin)
  - metals (aluminium, DC04, high strength steels (current tests))
  - wood (beech, multiplex, chipboards, MDF)



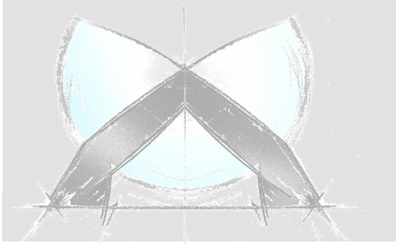


from:
4a Quartet card game "plastics"





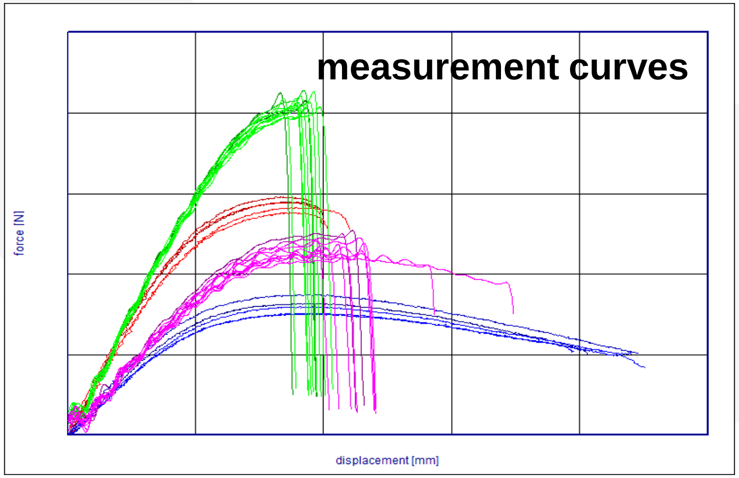
from:
4a Quartet card game "composites"

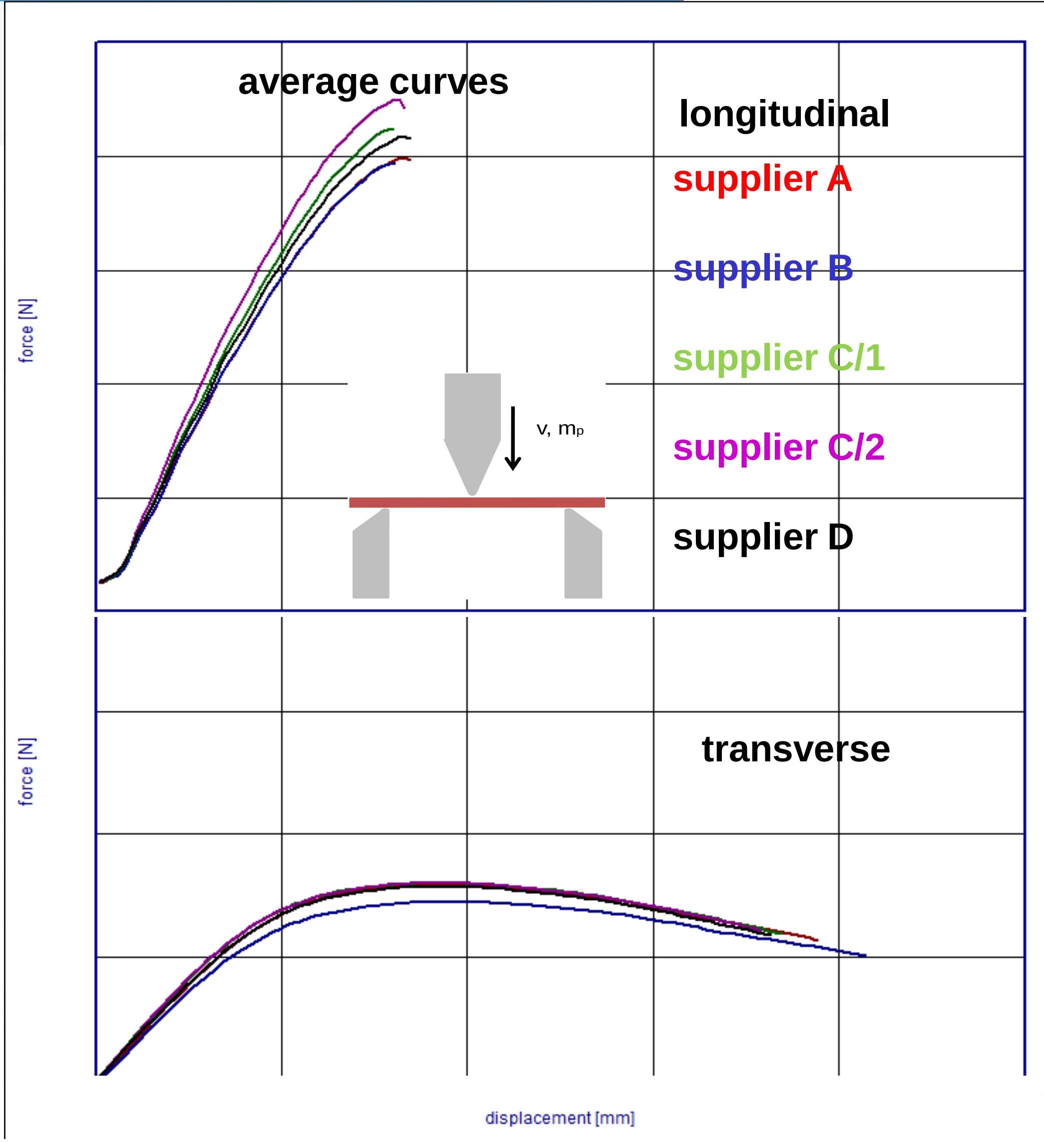


Applications
Quality control - comparison of supplier

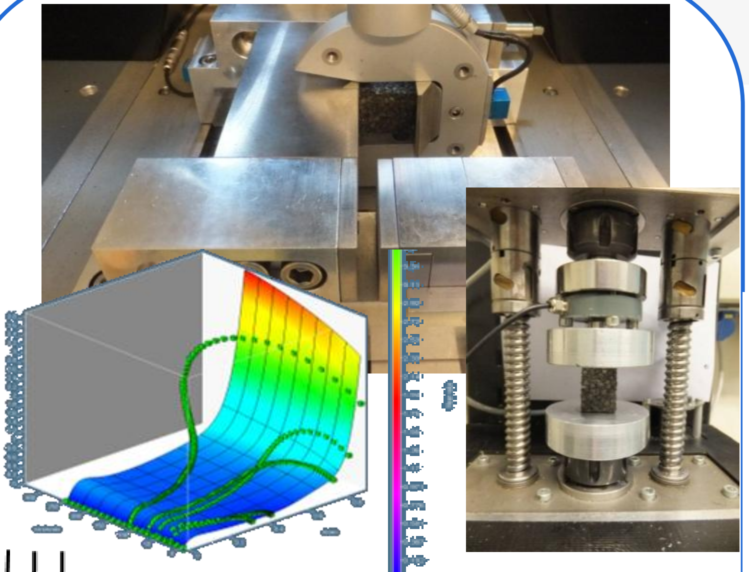
- Fast and easy comparison
  by instrumented impact test
- Accurate evaluation of
  force-displacement curve
- Bending test
  simple sample generation
  even out of a component
- Same evaluation

Averaging, filter, ….



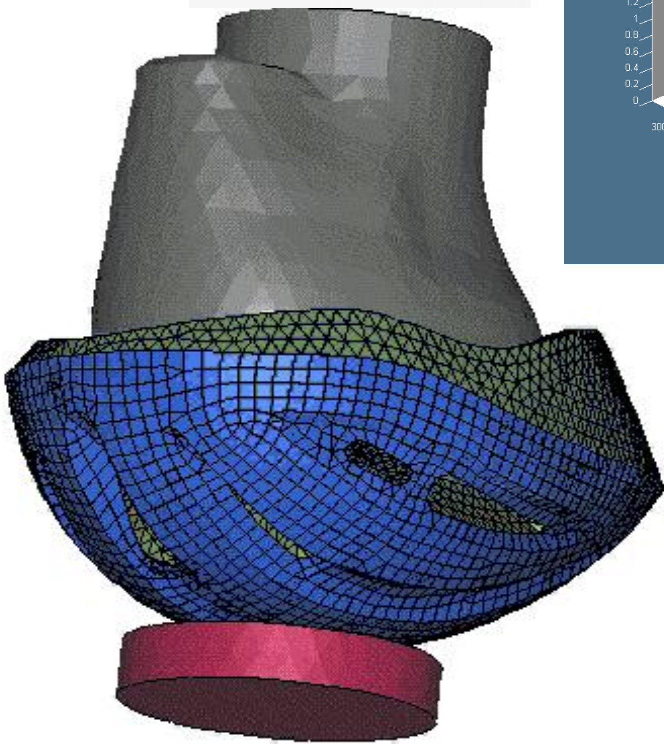


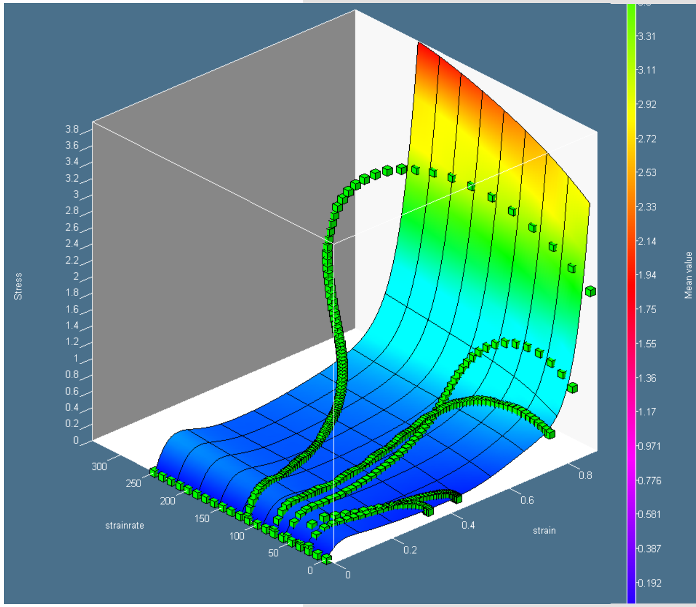
Applications
Material cards by compression tests



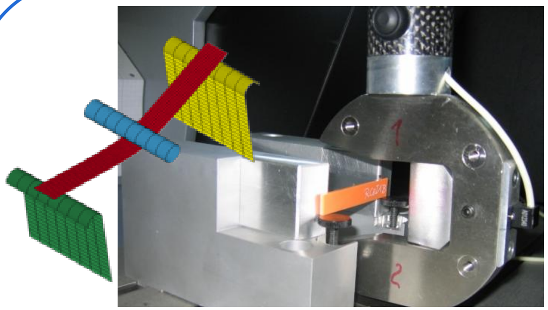
Foams(EPP, PUR, …)

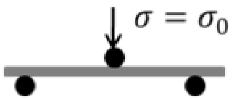
*MAT_LOW_DENSITY_FOAM
*MAT_FU_CHANG_FOAM
*MAT_SIMPLIFIED_RUBBER_FOAM





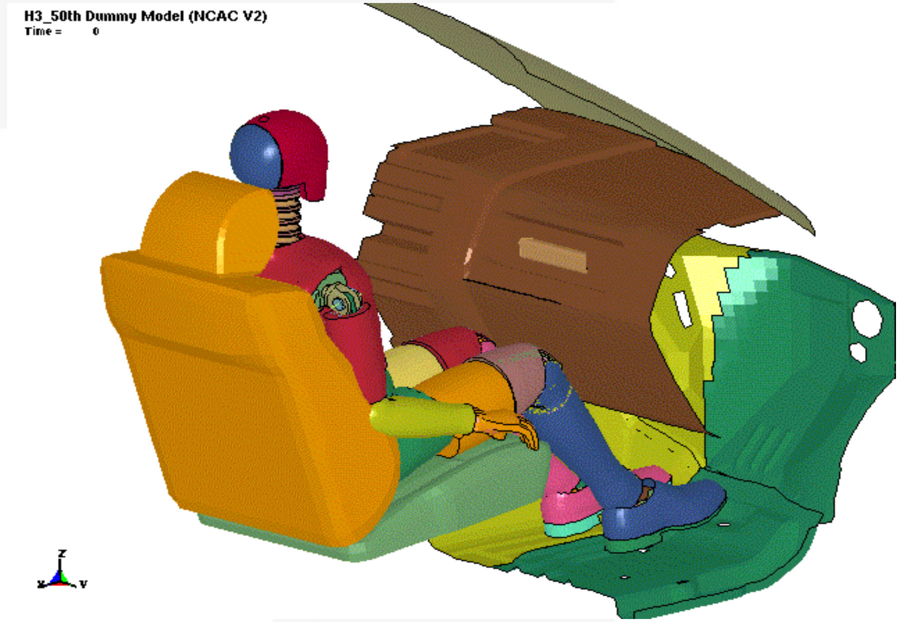
Applications
Material cards by 3-point-bending tests

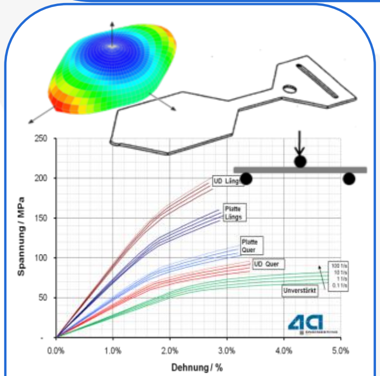




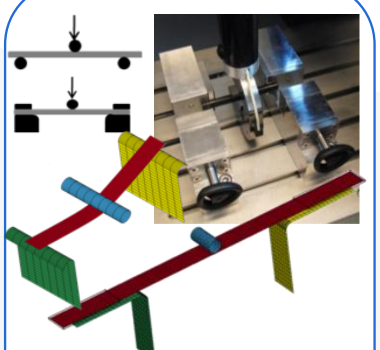
$$\sigma = \sigma_0 + E \cdot \varepsilon_p \cdot \frac{1}{\left[1 - \frac{E}{H} \cdot \varepsilon_p\right]}$$

Unreinforced plastics
(PA6, PBT, PE, PP, PC, ABS …)
*MAT_PIECEWISE_LINEAR_PLASTICITY

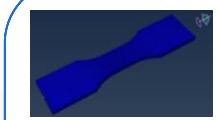


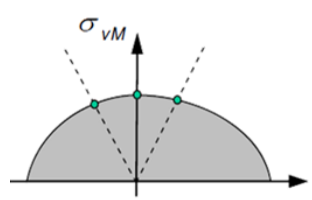


Reinforced plastics
(PP GF, PA6 GF, PBT GF…)
*MAT_24 for exposed directions



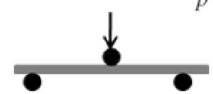
Unreinforced plastics
(PA6, PBT, ABS, PP …)
*MAT_PLASTICITY_
COMPRESSION_TENSION





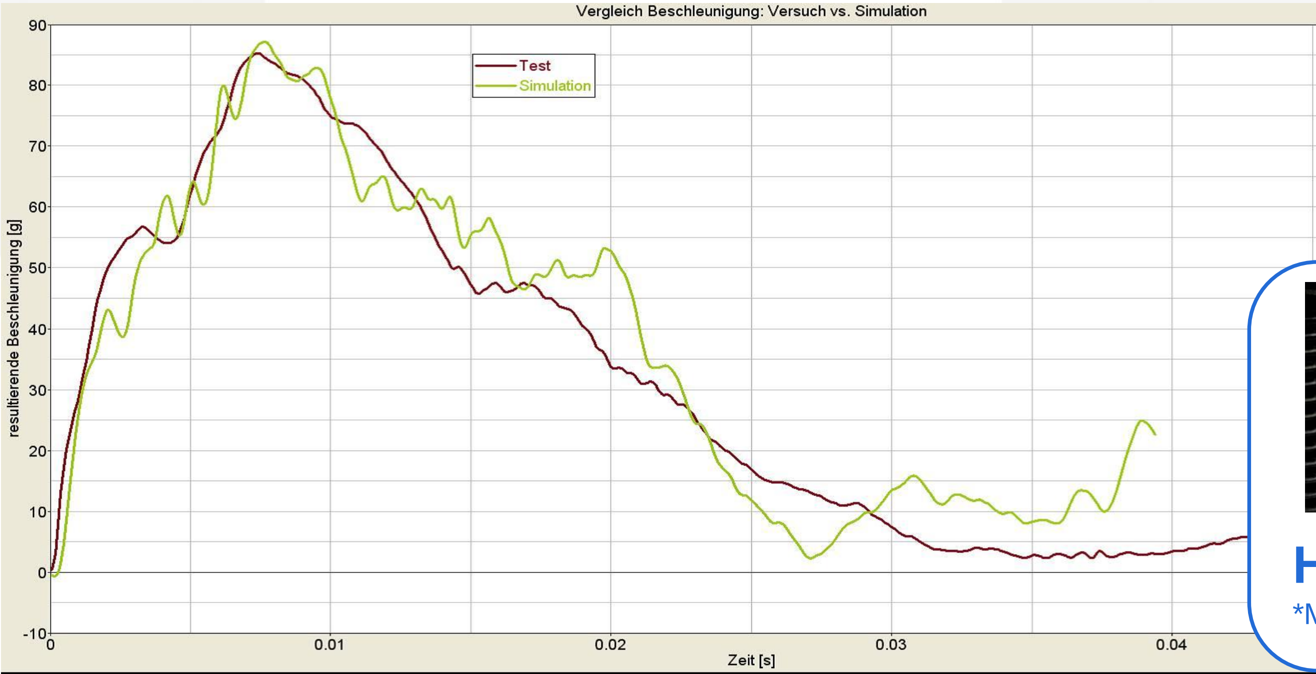
Unreinforced plastics
(PA6, PBT, ABS, PP …)
*MAT_SAMP-1

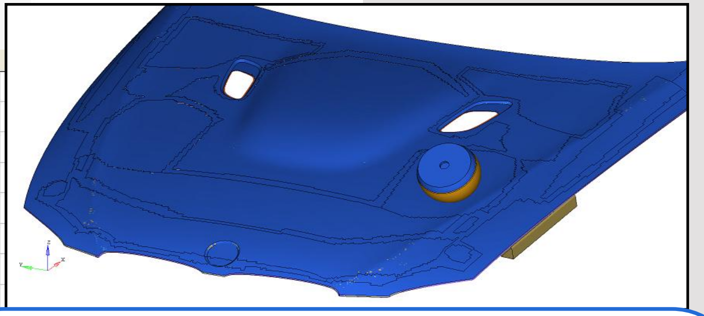
$$\sigma = A + B\varepsilon_p^n$$

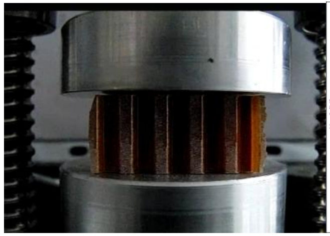


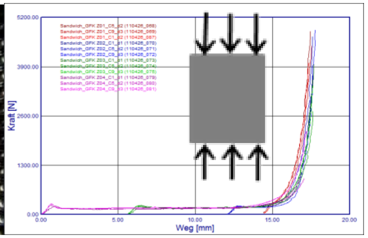
Metals
(DC04, ALU 6000, …)
*MAT_PIECEWISE_LINEAR_PLASTICITY

Applications
Material cards composites – front hood









Honeycomb (Nomex, …)

*MAT_LOW_DENSITY_FOAM

Applications
Component testing

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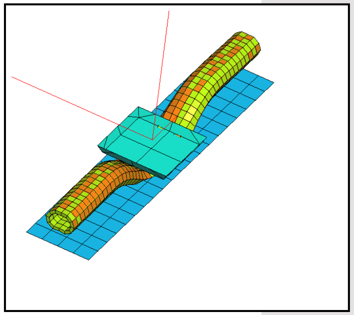
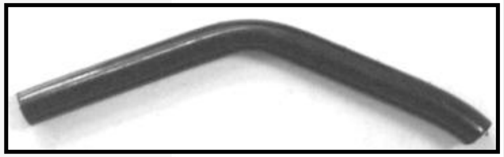
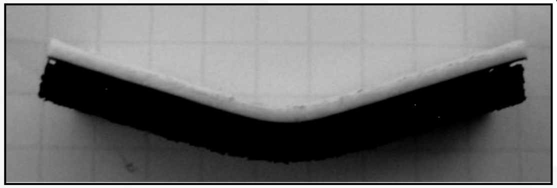
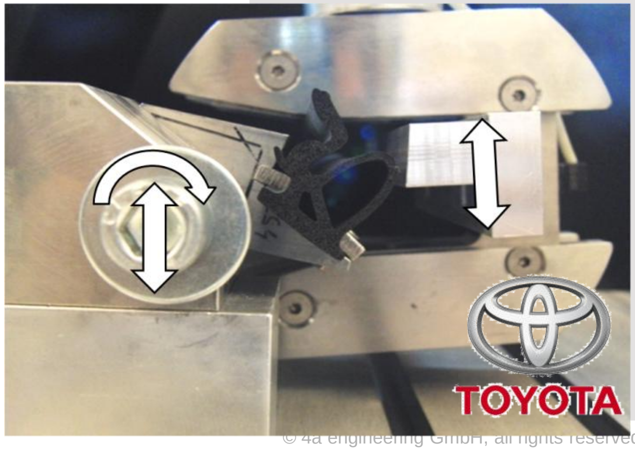
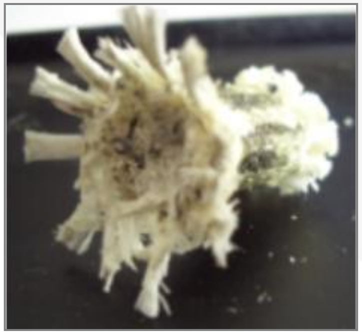
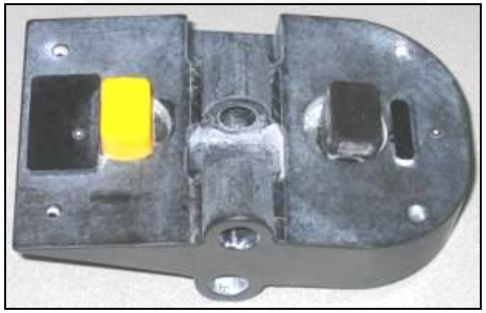
- Weather strip
- Wire harness
- Water hose
- Brake tube
- Air bag module
- Sun shield
- Foamed parts
- Swirl body
- Multi layer composites







Hardware

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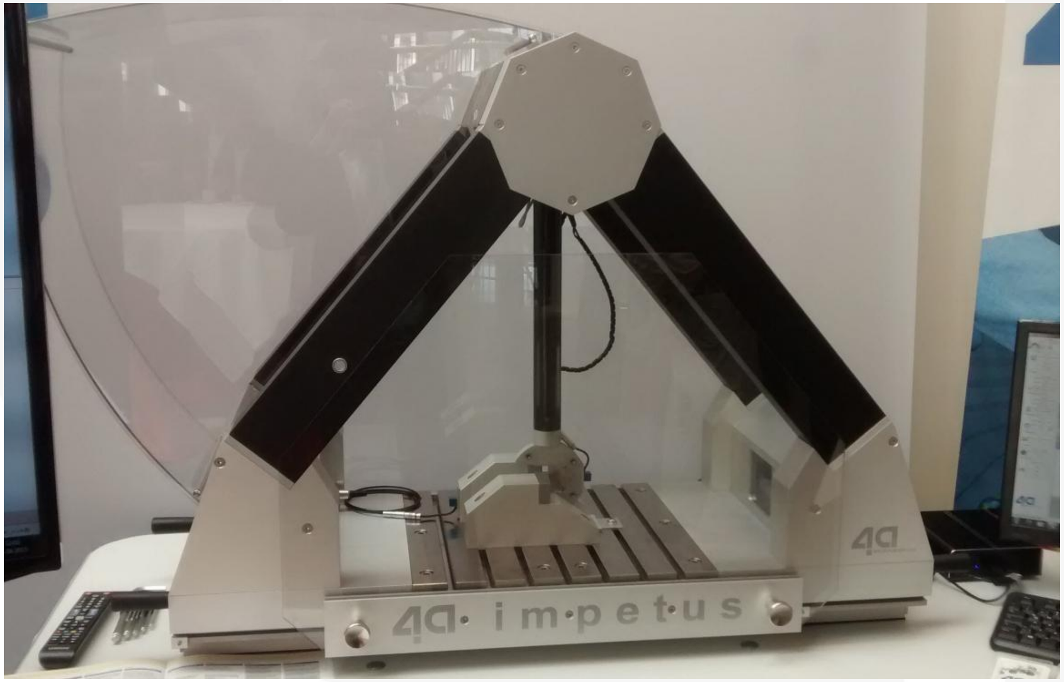
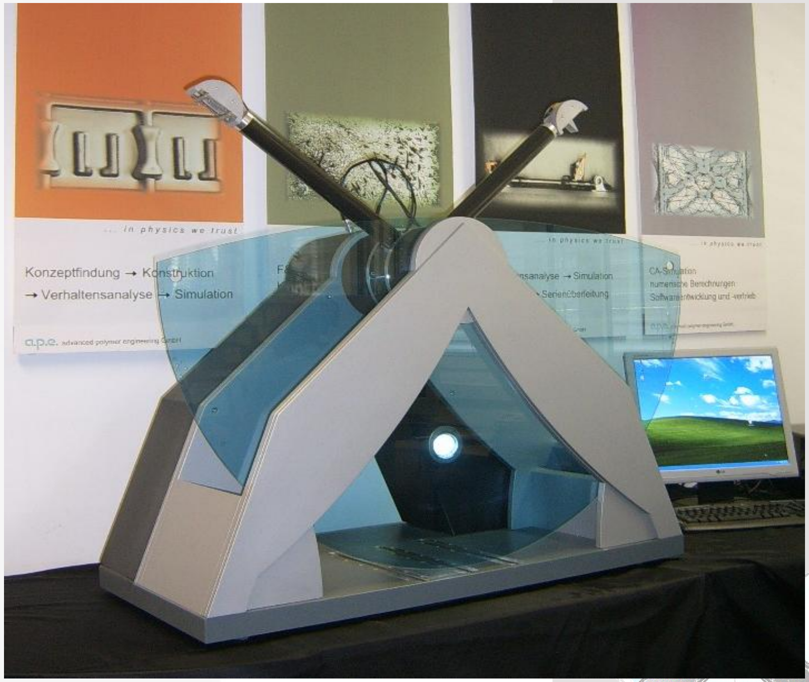
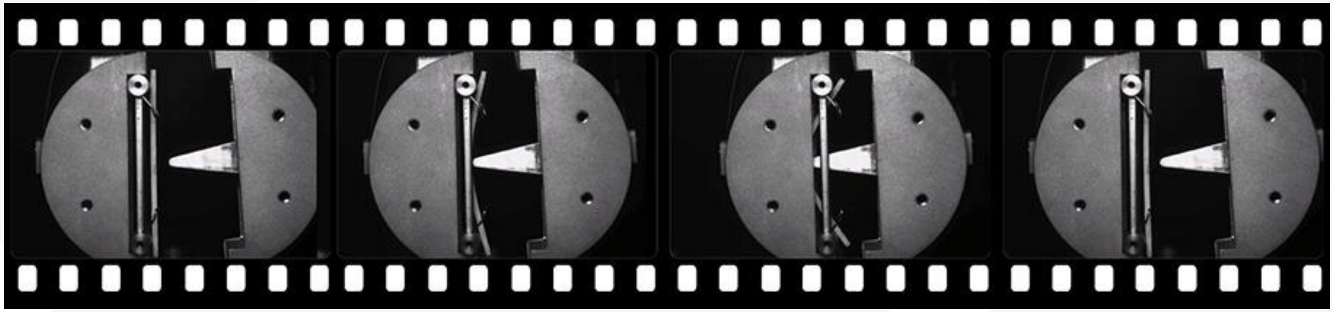
Single and double pendulum

- Single pendulum **0.5 - 4.5 m/s**
  - maximum energy ~20J (changing introduced energy by adding mass)
  - maximum energy ~50J in work
  - maximum acceptable acceleration 2000 g
- Double pendulum **unique selling point 0.5 - 8 m/s**

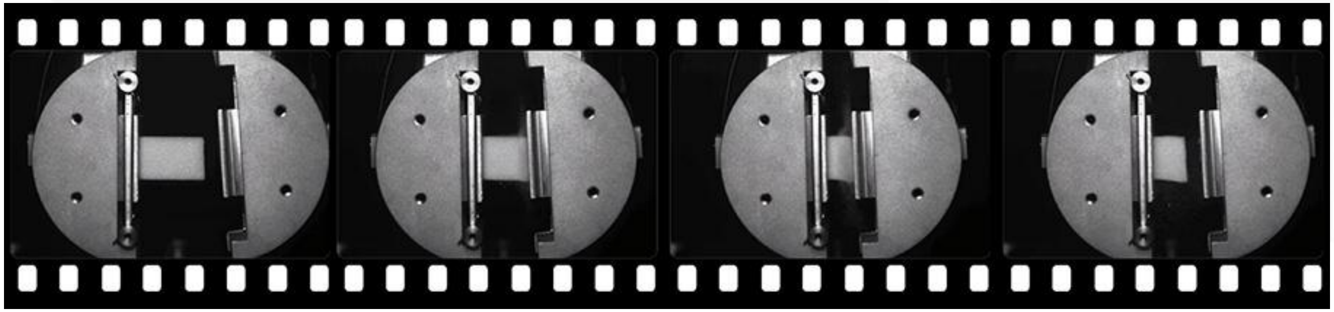




- Compression test (foam materials)
- Bending test (solid materials)
- Clamped bending test (dominating part: tension)
- Puncture test (biaxial loading, failure)
- Quasi-static tests are made in addition by default
- Double pendulum:



dynamic 3-point-bending



dynamic compression

Measurement technique

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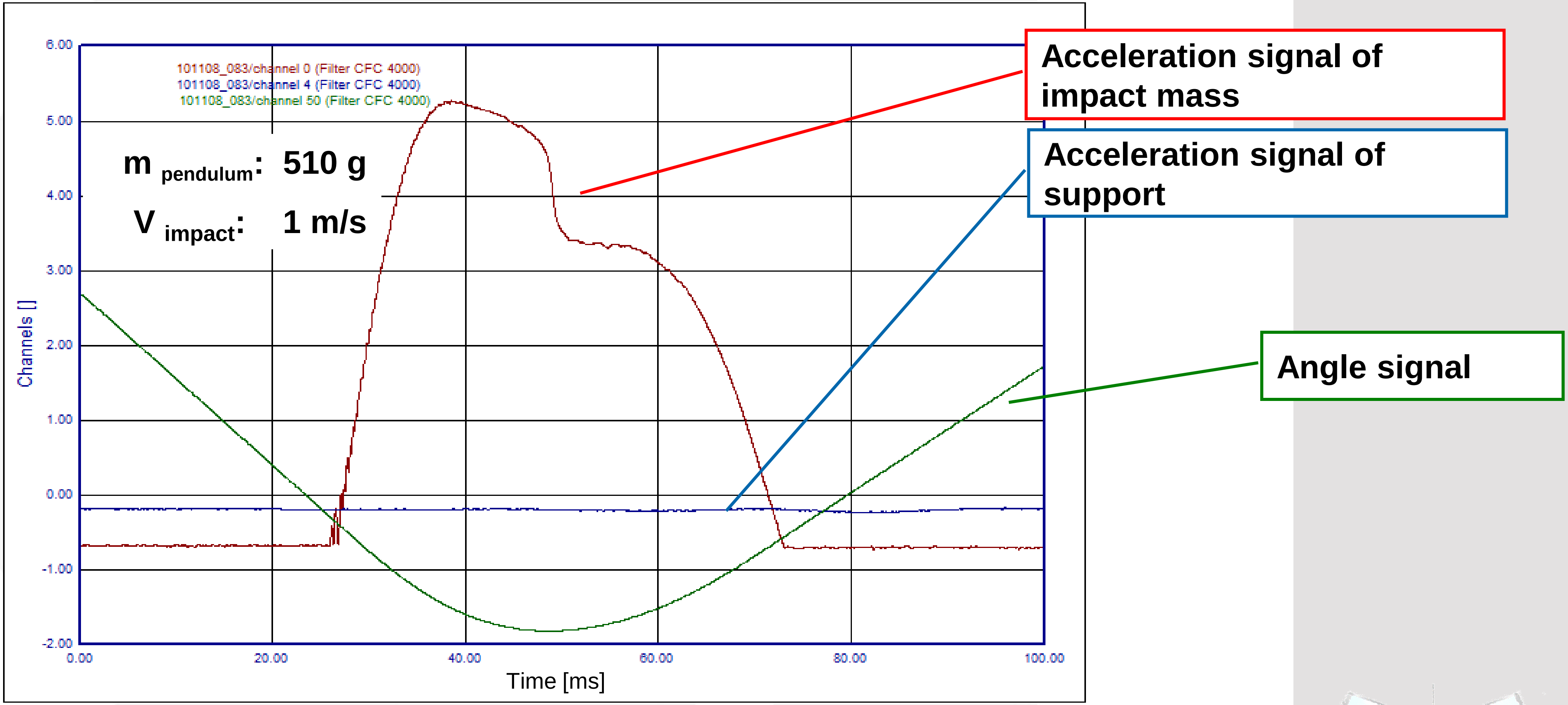
Measurement technique

4a impetus - dynamic 3-point-bending



The deceleration of the pendulum arm and the rotation angle of the shaft are measured. This allows a very exact determination of dynamic force/replacement-characteristics.

Measurement technique
Analog/digital converter

- Using 16 bit and up to 2 MS/s total sampling rate for analog channels. For a velocity of 5 m/s you have a resolution of **400 samples/mm**. So also **brittle materials can be tested** and **natural frequencies** of test specimens can be measured.
- A separate digital 32-bit counter at the data measurement device allows the use of digital rotary transmitter and facilitates the analog sampling.

Measurement technique
Incremental rotary transmitter

- Very exact sensor resolution **320.000 points / turn**
  → theoretical resolution **0.01 mm** in the circular path of the pendulum
- Sensor doesn‘t have a dead range
- 0-pulse of the rotary transmitter can be used as trigger for the measuremen
- possibility of evaluation: displacement out of the angle → calibration of the system

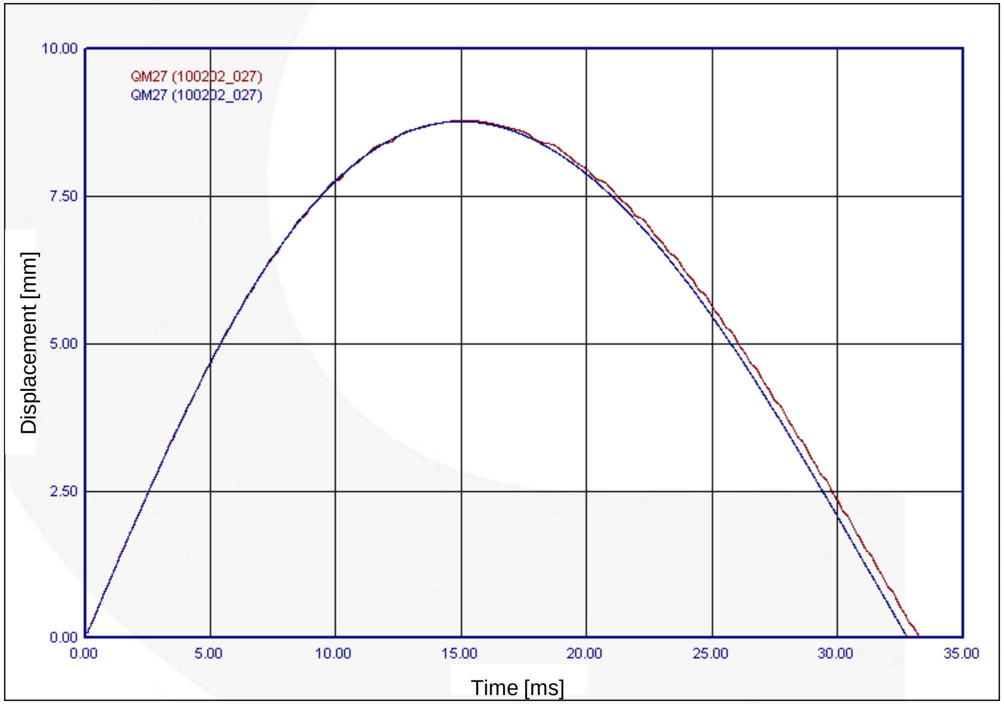
Measurement technique
Incremental rotary transmitter

Calculation of the displacement

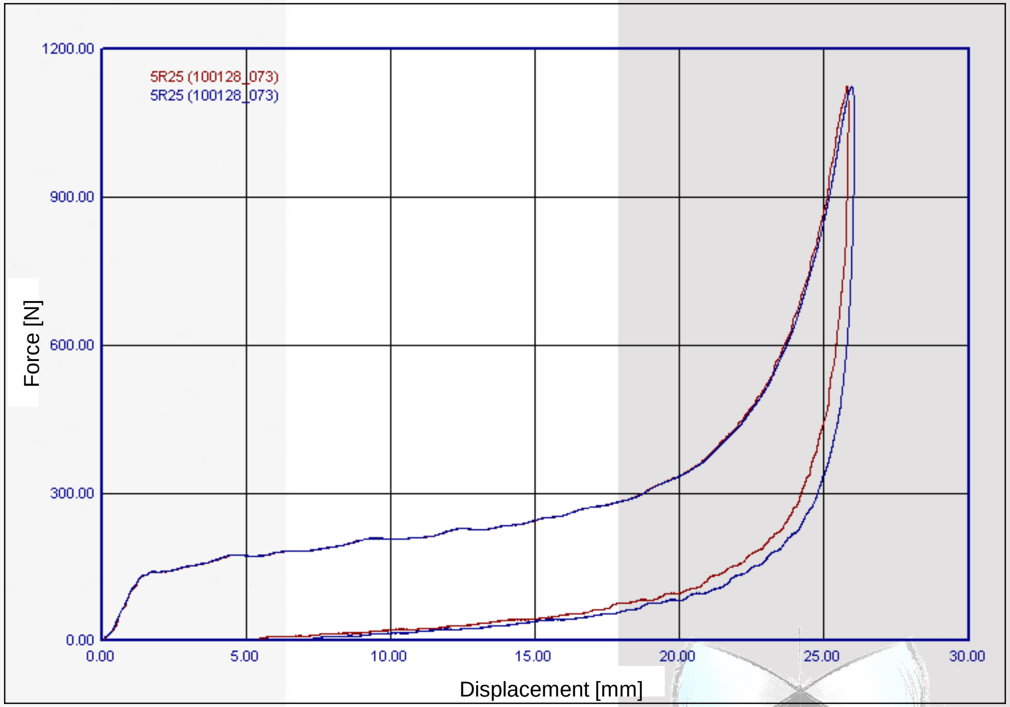
Evaluation out of the angle signal vs. acceleration signal

Calibration of the system using the angle signal vs. acceleration signal is possible

3-point-bending test 1mps

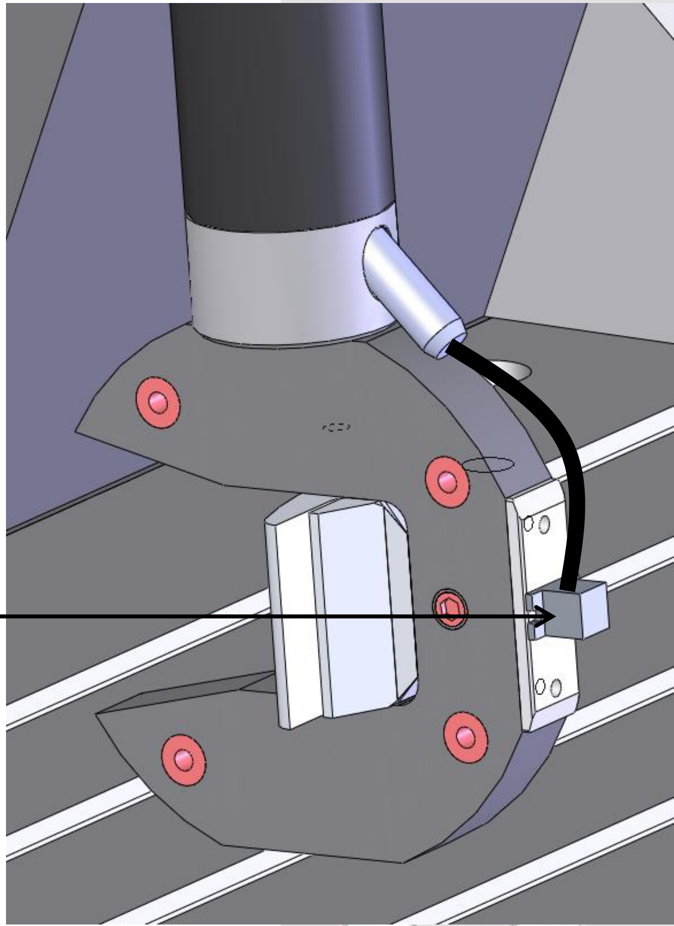


compression test for foam 3.5mps



Measurement technique
Acceleration sensors

Concept using plug-in sensors



- Piezo resistive sensors (50g - 1000g)
- Capacitive acceleration sensors
  - 5g – 400g
  - Temperature compensated
  - Low noise option available
- accuracy of 1% in the measurement range of 10% - 100%.

<u>Advantages:</u>

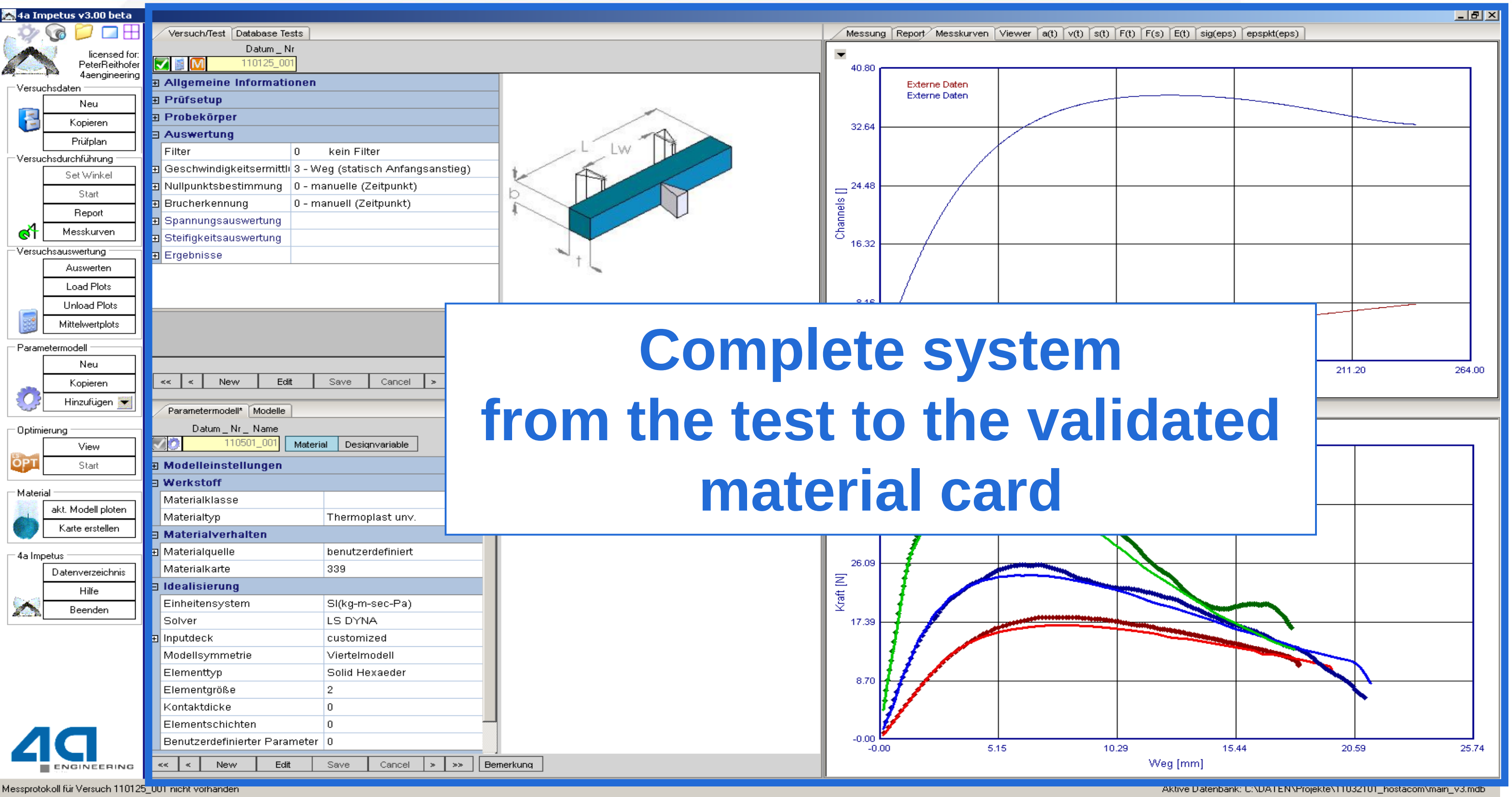
- **Exchangeable sensors →** individual measurement range
- Quick change of the acceleration sensor („**plug and test**“) – 2 screws
- Simple distribution for calibration

Temperature and moisture sensor is also included.

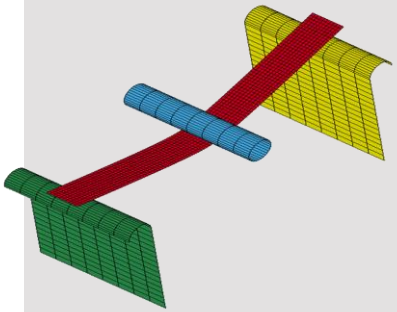
Software

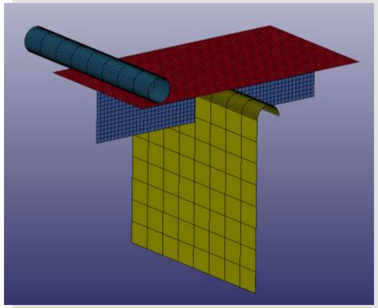
4a impetus software

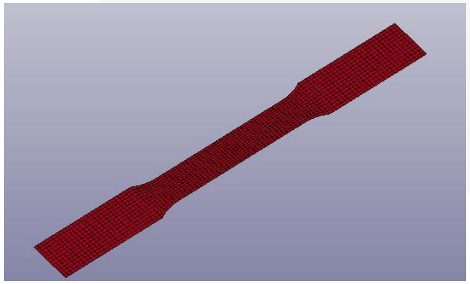
Software solution from the test to the material card

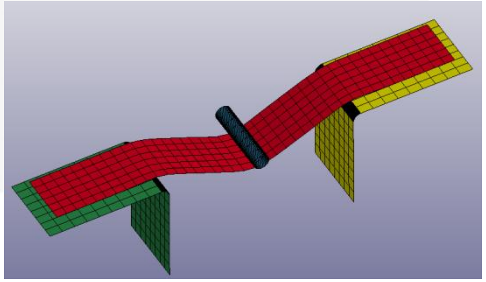


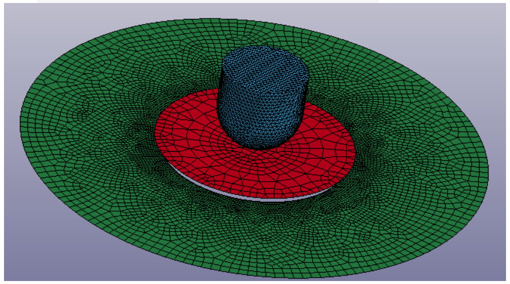
Complete system from the test to the validated material card

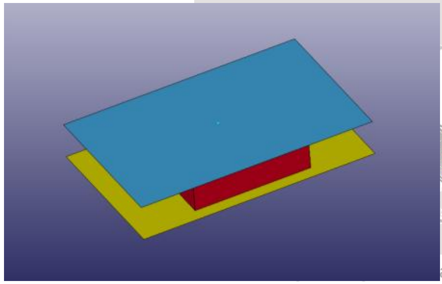






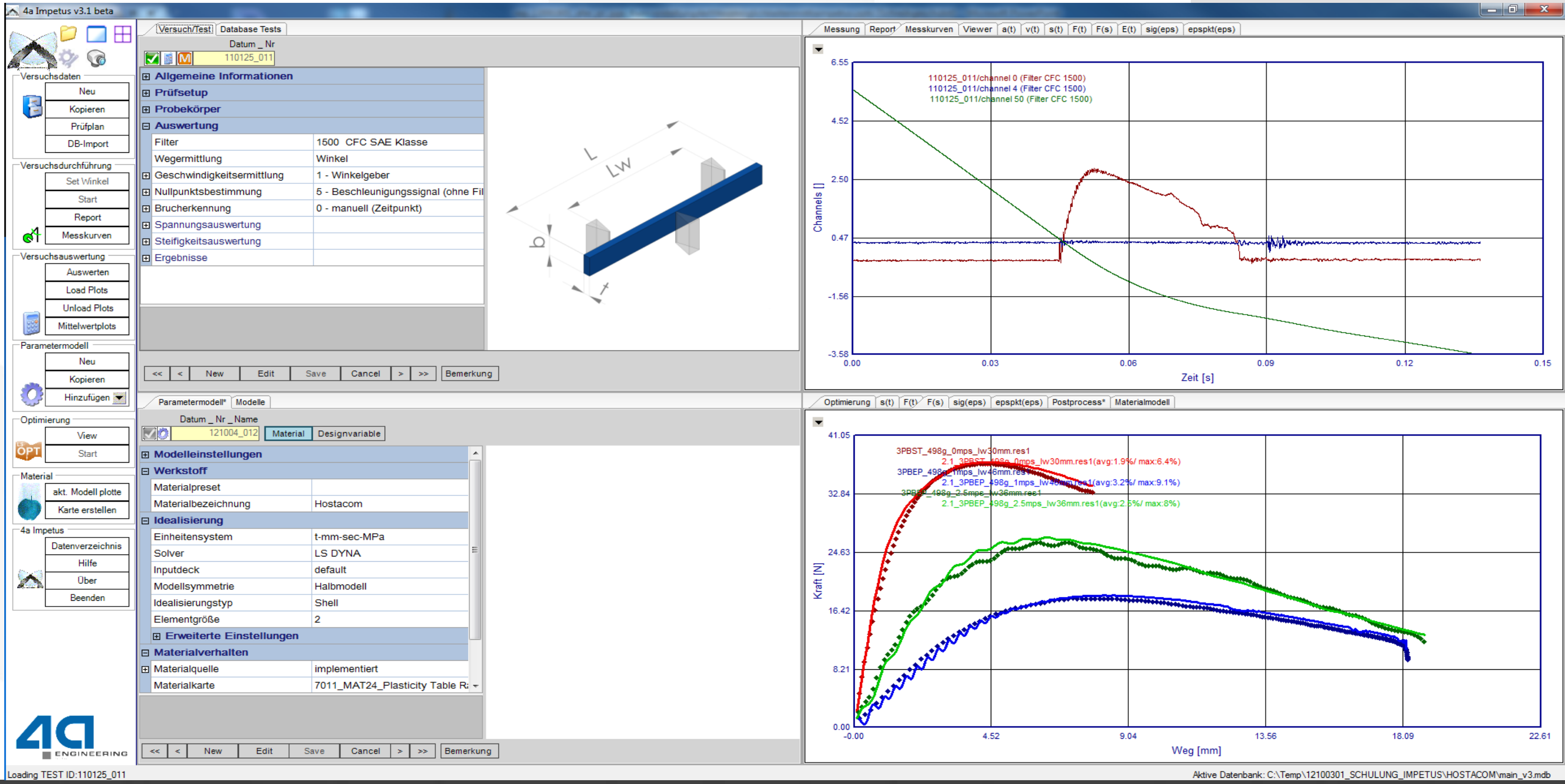




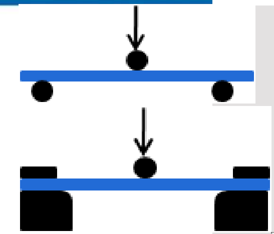


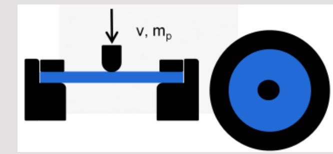
4a impetus software
Process / functional range

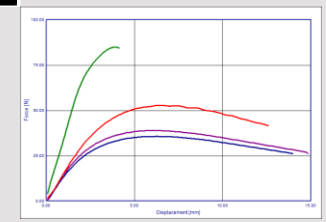
- Test plan setting
- Performing measurements (only 4a impetus hardware)
- Evaluation of the measurements
- Measurement results
- Import of external measurement results
- Model build up
- Material models
- Optimization



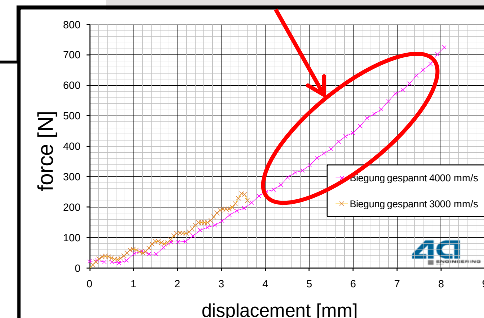
- 4a impetus is a pendulum test device to characterize materials by (clamped) 3-point-bending, compression and puncture tests
- Capturing different strain rates and the strain rate dependency
  - changing the pendulum speed and/or changing the support distance
- Capturing compression/tension behavior
  - import quasi-static tensile (and shear and compression) test
  - clamped bending test
- Capturing loading / unloading → damage
  - 3-point-bending test
  - Multiple loading clamped bending test
- Capturing failure
  - Clamped bending test → uniaxial; puncture test → biaxial
- Capturing component test → T-specimen

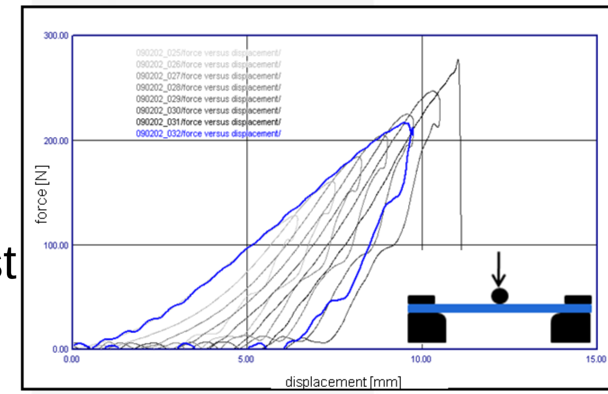


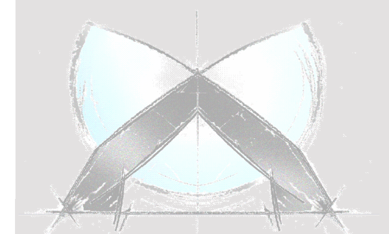




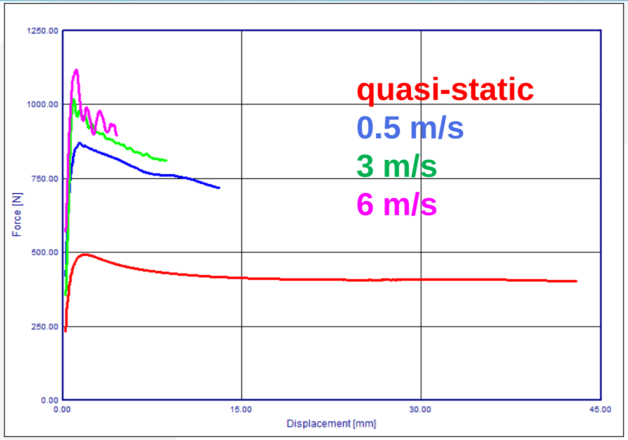
tension dominated



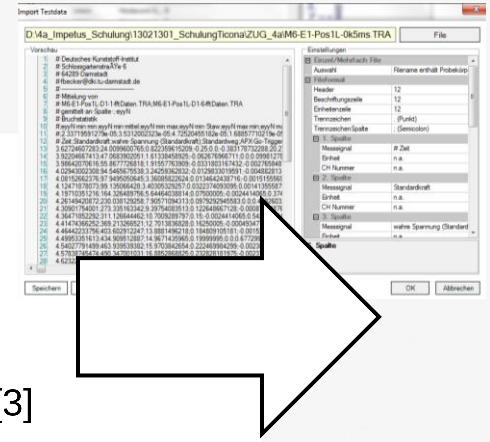


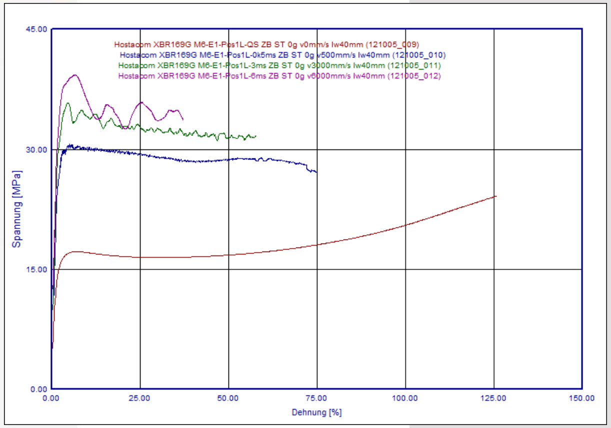


4a impetus
Import test results from different sources



[3]





measured force/displacement curves on tensile testing machine

import

evaluation of stress/strain curves

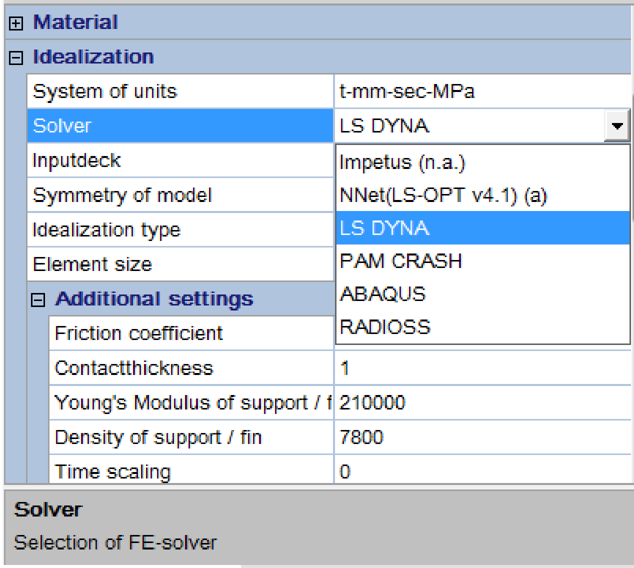
Using the 4a impetus software the user can

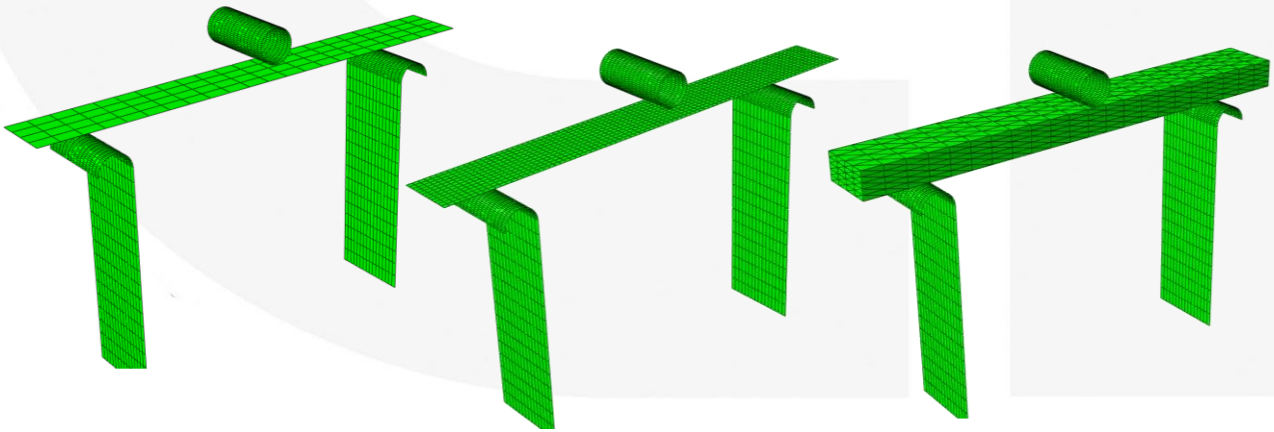
- Import additionally any other tests (e.g. quasi-static bending, tensile or compression test, any supplier) into the test data base (e.g. force/displacement curves),
- Evaluate all the tests (also the imported ones) and use these data only or additional for generating the material card or calculate the test curves using the material card (validation).

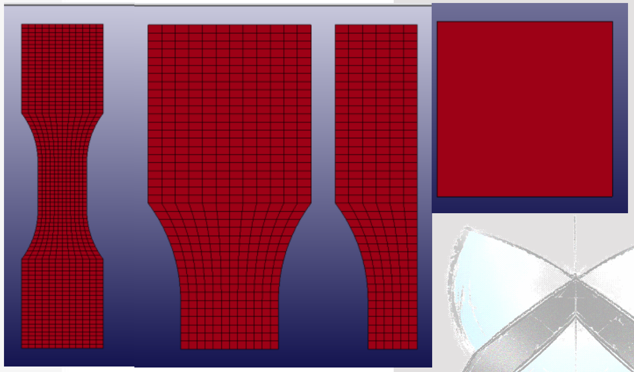
4a impetus

Simulation - Idealization

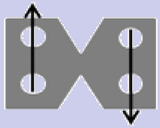
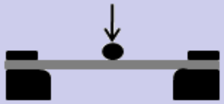
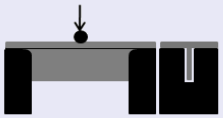
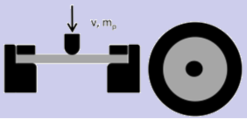
- Can be used local or in network
- Supports LS-Dyna, Abaqus, PAM-Crash, Radioss
- Allows the idealization in shell or solid using the most popular element types and an arbitrary element size (of course it should be reasonable)
- Can consider symmetries – simplification down to 1-element







4a impetus
Available test methods - Interfaces in 4a impetus V3.2

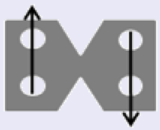
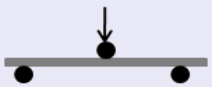
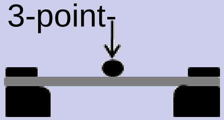
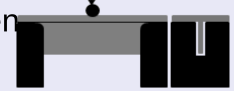
	ABAQUS	LS-DYNA	PAMCRASH	RADIOSS
	implicit / explicit	implicit / explicit	explicit	
	implicit / explicit	implicit / explicit	explicit	
	implicit / explicit	implicit / explicit	explicit	
	implicit / explicit	implicit / explicit	explicit	explicit
	implicit / explicit	implicit / explicit	explicit	explicit
	implicit / explicit	implicit / explicit	explicit	explicit
	implicit / explicit	implicit / explicit	explicit	

in progress

implemented

tested

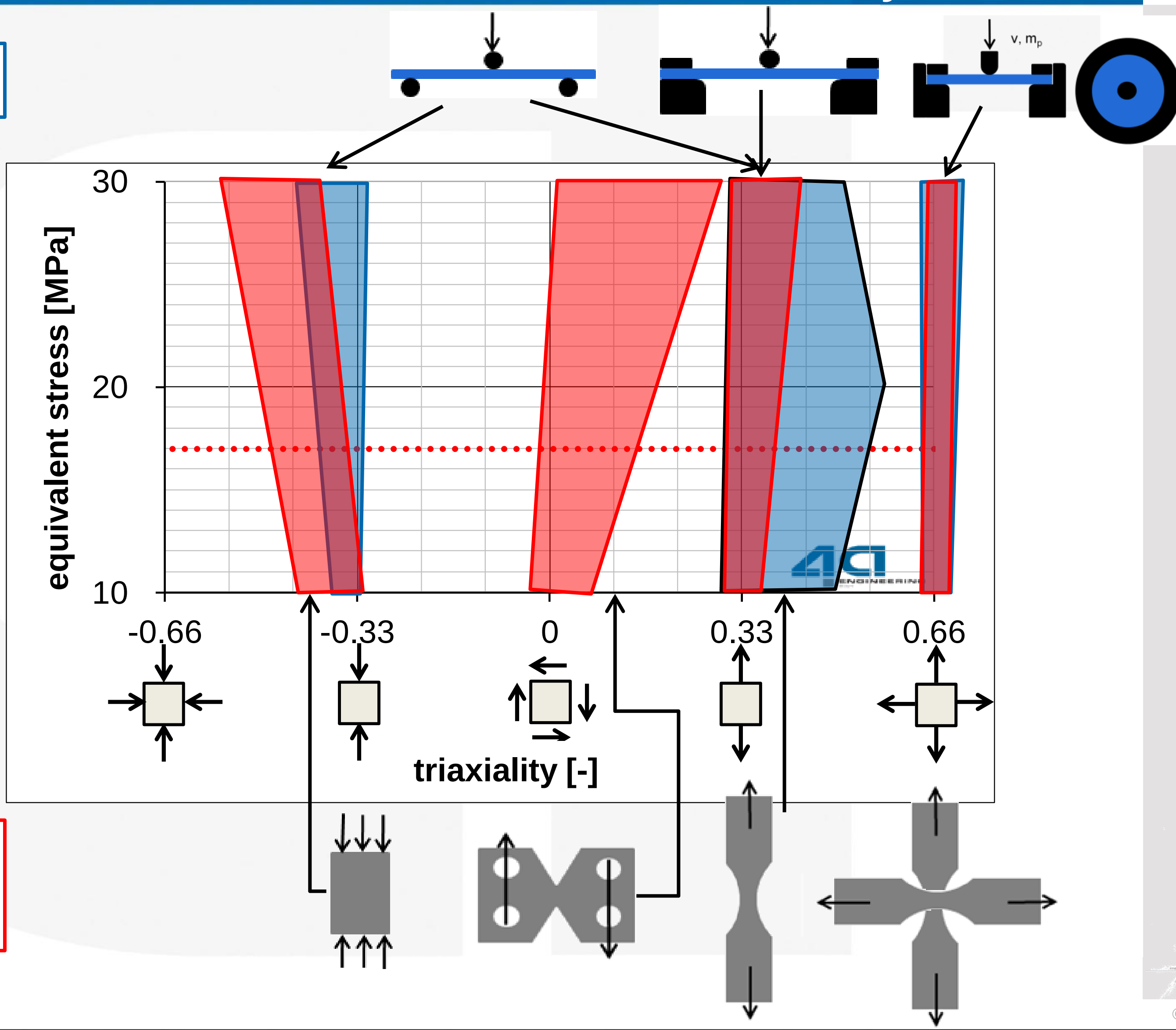
4a impetus
Generating material cards – different approaches

	classic approach		4a impetus		
	*MAT_24	*MAT_187	*MAT_24	*MAT_124	*MAT_187
tensile test 	static and dynamic tests	static and dynamic tests		static tests	static tests
compression 		static tests			
shear 		static tests			
biaxial tension puncture test		static tests			
3-point-bending 			static and dynamic tests	static and dynamic tests	static and dynamic tests
clamped 3-point-bending 				dynamic tests	dynamic tests
bending using T-specimen 	Also possible with 4a impetus software				

4a impetus

Generating material cards – influence of triaxiality

4a impetus



Classic approach

Generating material cards - LS-Dyna material models

- 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 — general yield surface

Material behaviour	
Material source	Implemented
Density	-1020.83
Poisson's ratio	0.3
Failure strain	0
Elasticity	Linear elastic
Plasticity	vonMises
Curve 1	4a Model A
Strain rate dependency	Table
Strain range upto	0.25
Sampling points	50
Bias factor	10
Material card	7011_MAT24_Plasticity Table Rate log. Table

Material behaviour	
Material source	Implemented
Density	-1020.83
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 range upto	0.25
Sampling points	50
Bias factor	10
Material card	7021_MAT124

Material behaviour	
Material source	Implemented
Density	-1020.83
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 range upto	0.25
Sampling points	50
Bias factor	10
Material card	7031_MAT187

- All LS-DYNA material cards are available using user defined interfaces!
- Same possibilities for the other solvers (e.g. Abaqus, PamCrash,…)

4a impetus
Generating material cards

- ➢1st step: performing static and dynamic bending tests
- ➢2nd step: evaluation of the data
- ➢3rd step: material characterization – identification of the parameters using LS-OPT

Young's Modulus

↓

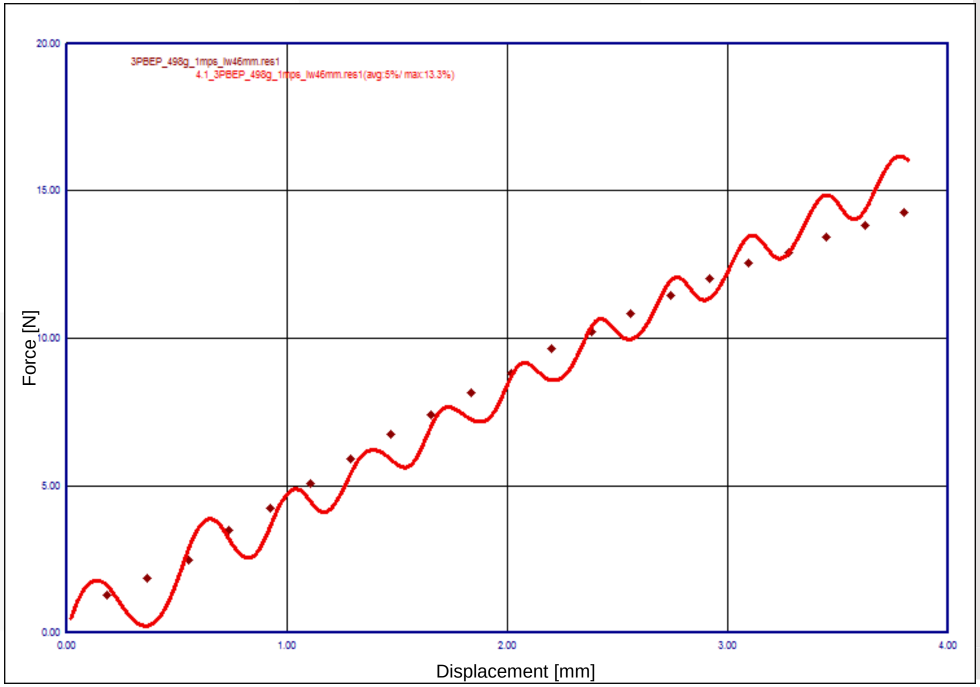
plastic characteristics

↓

strain rate dependency

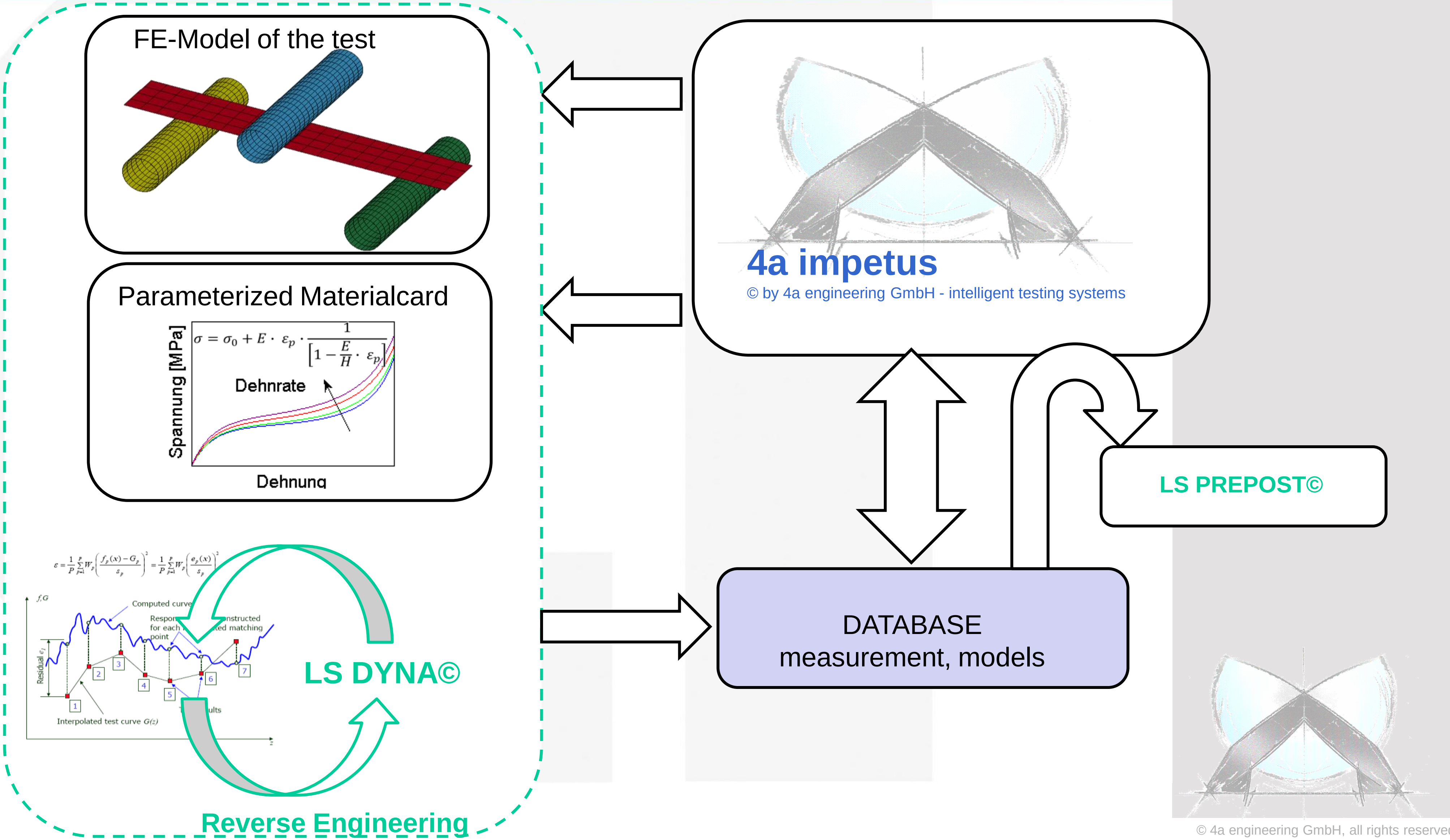
↓

validation



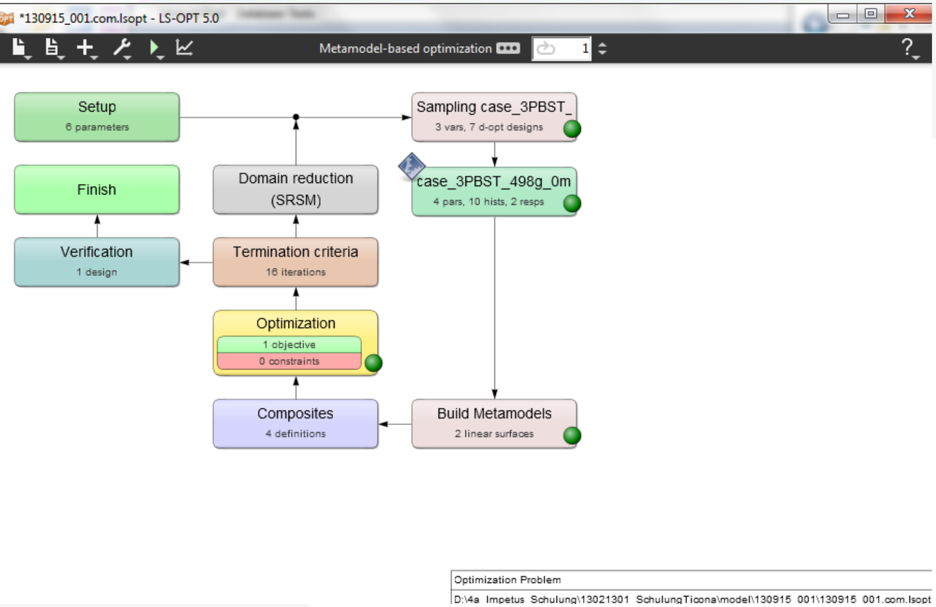
I N P H Y S I C S W E T R U S T

4a impetus
Reverse Engineering

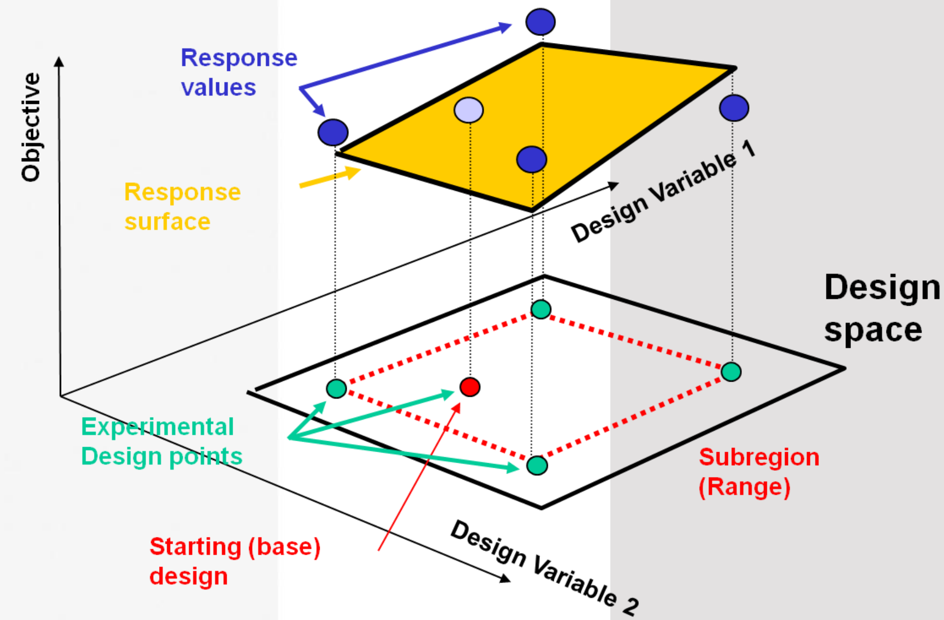


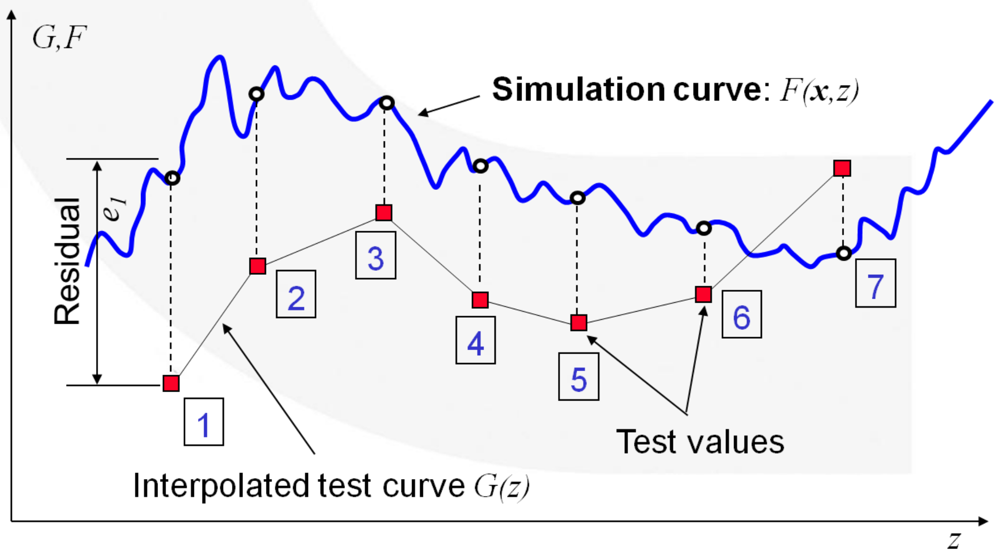
4a impetus

Reverse Engineering – LS-Opt process



Sequential Response Surface Method



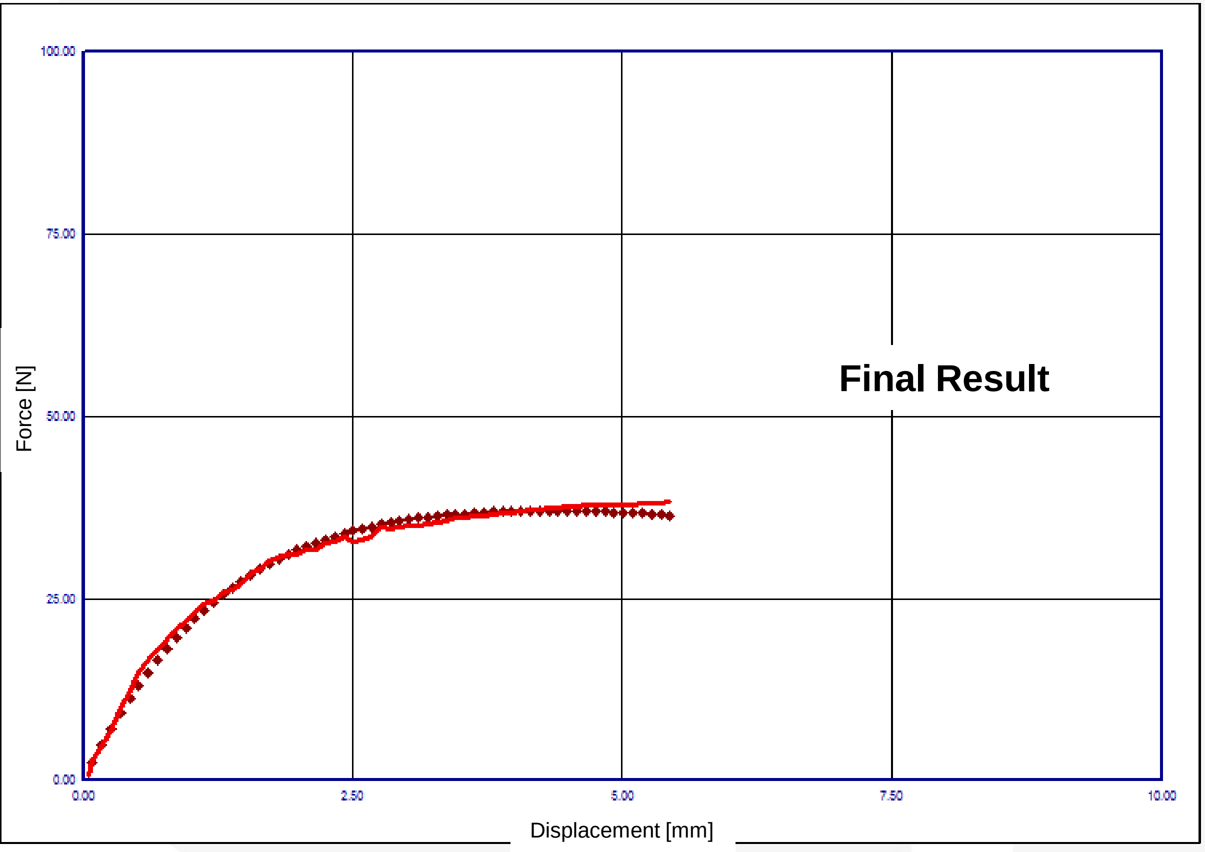


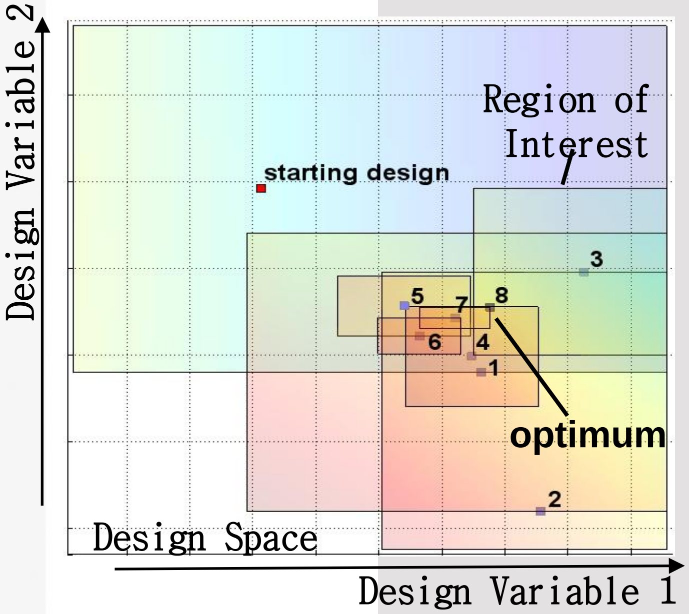
Mean Squared Error

$$MSE(\mathbf{x}) = \frac{1}{P}\sum_{i=1}^{P} W_i \left(\frac{F_i(\mathbf{x}) - G_i}{s_i} \right)^2 \rightarrow \min$$

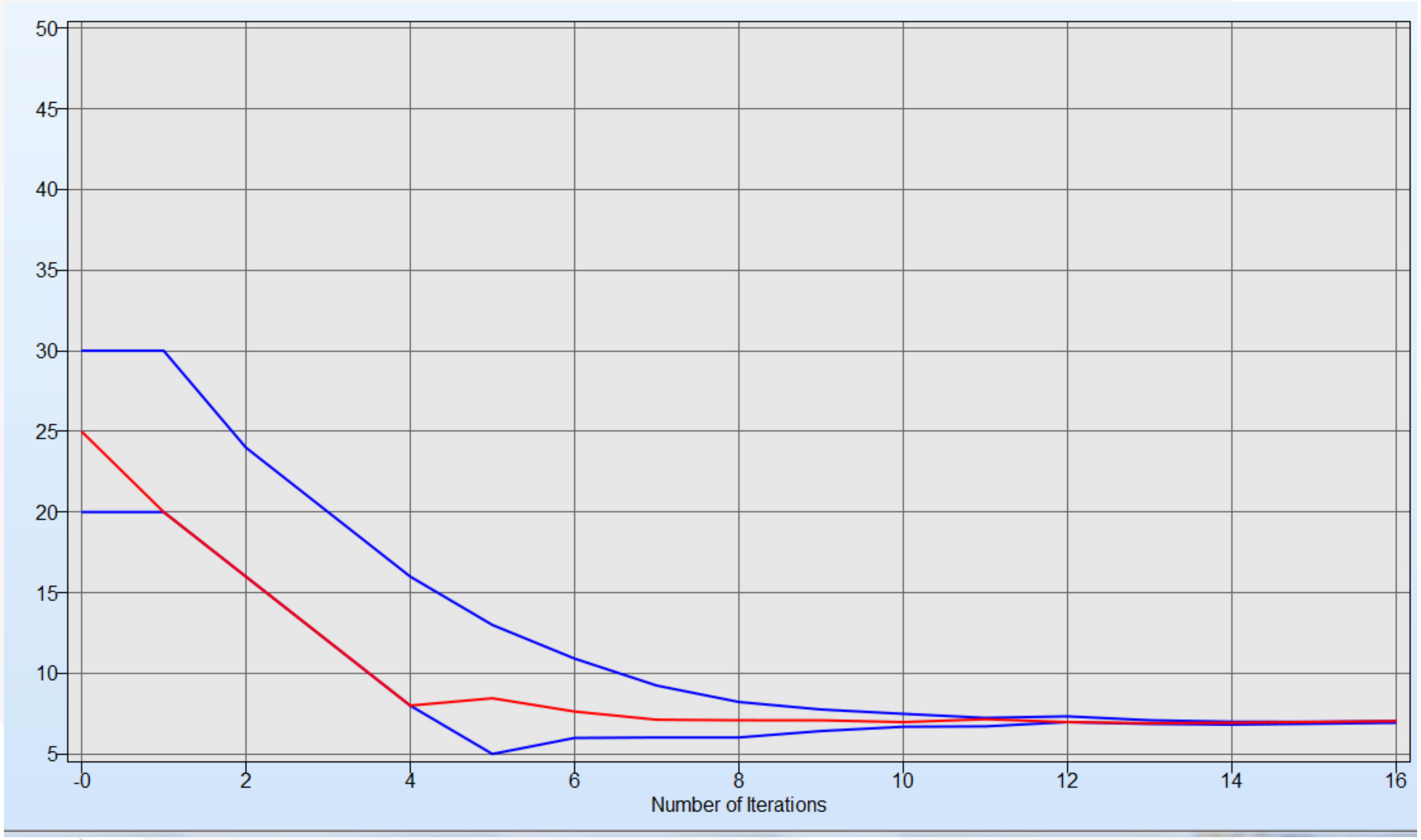
[4]

➤ 3rd step: material characterization - plastic characteristics





- Development of the design variable σ_y



- 1st step: performing static and dynamic bending tests
- 2nd step: evaluation of the data
- 3rd step: material characterization – identification of the parameters using LS-OPT

Young's Modulus

↓

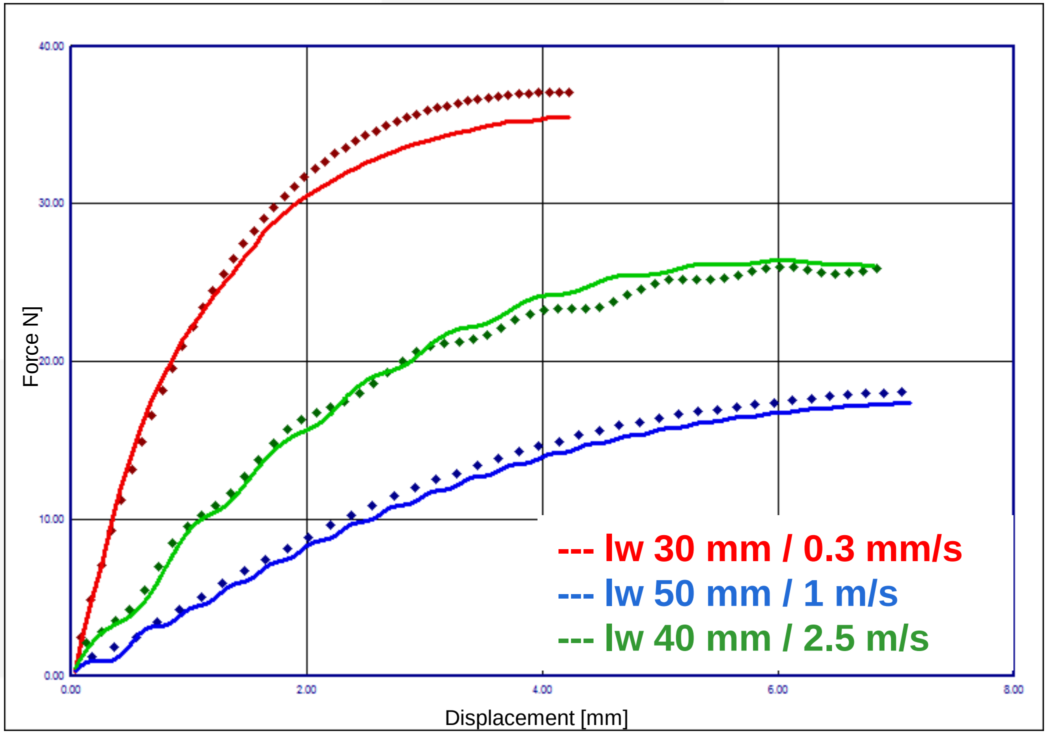
plastic characteristics

↓

strain rate dependency

↓

validation



4a impetus

Generating material cards

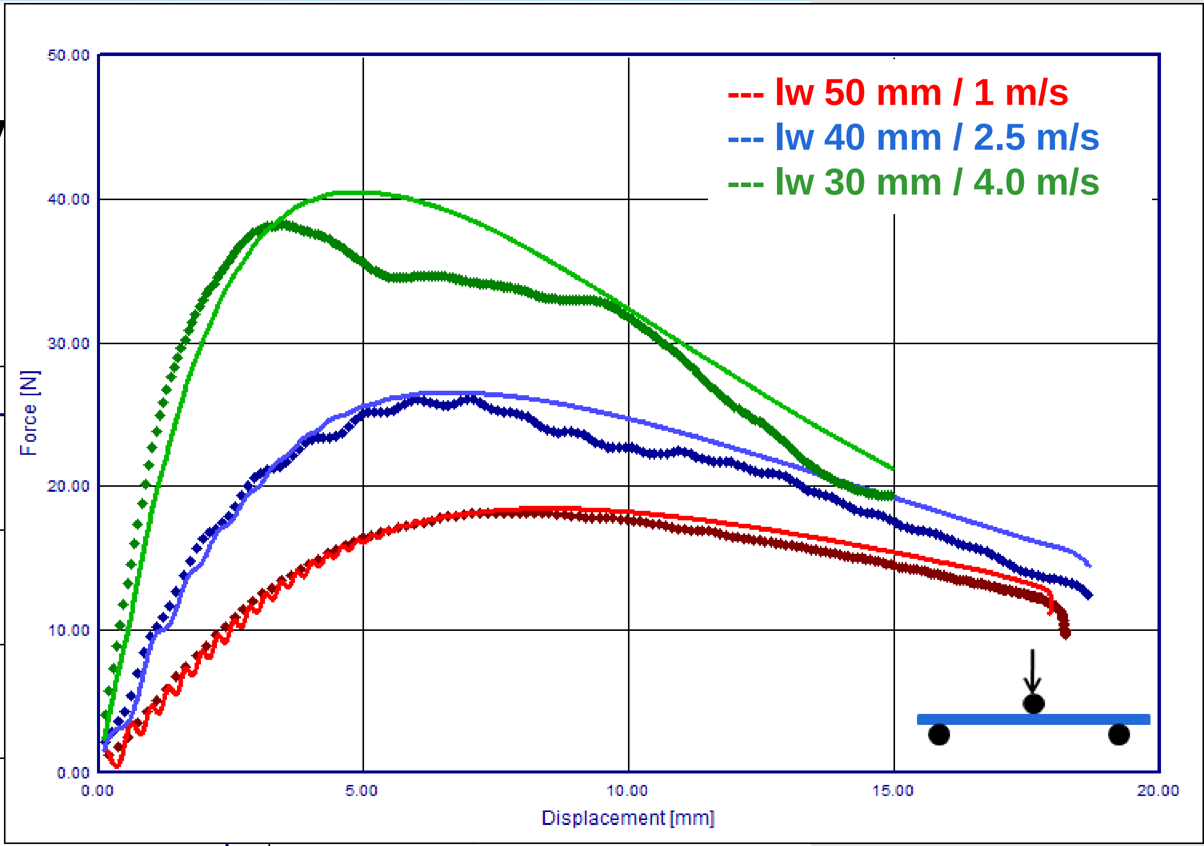
4a ENGINEERING GmbH

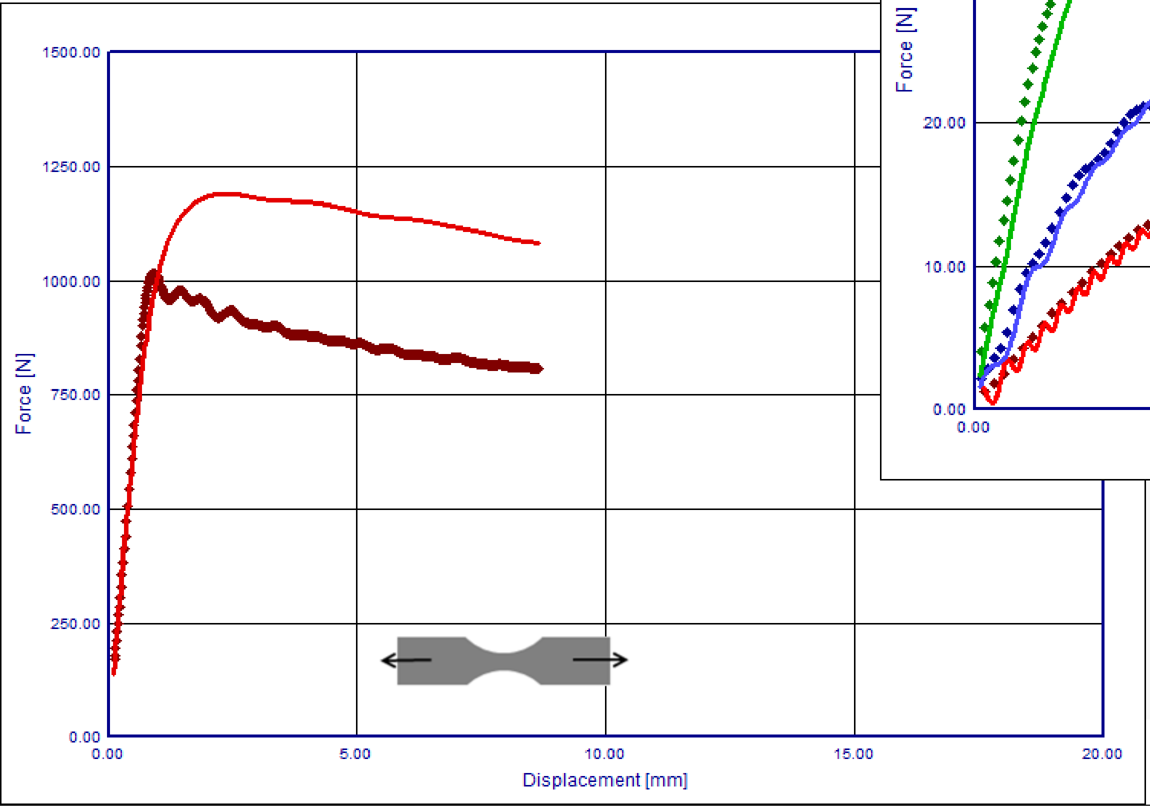
- LS-Dyna: *MAT24 (von Mises)
- **No tension/compression asymmetry**

  → good conformity for bending

  → poor conformity for tension

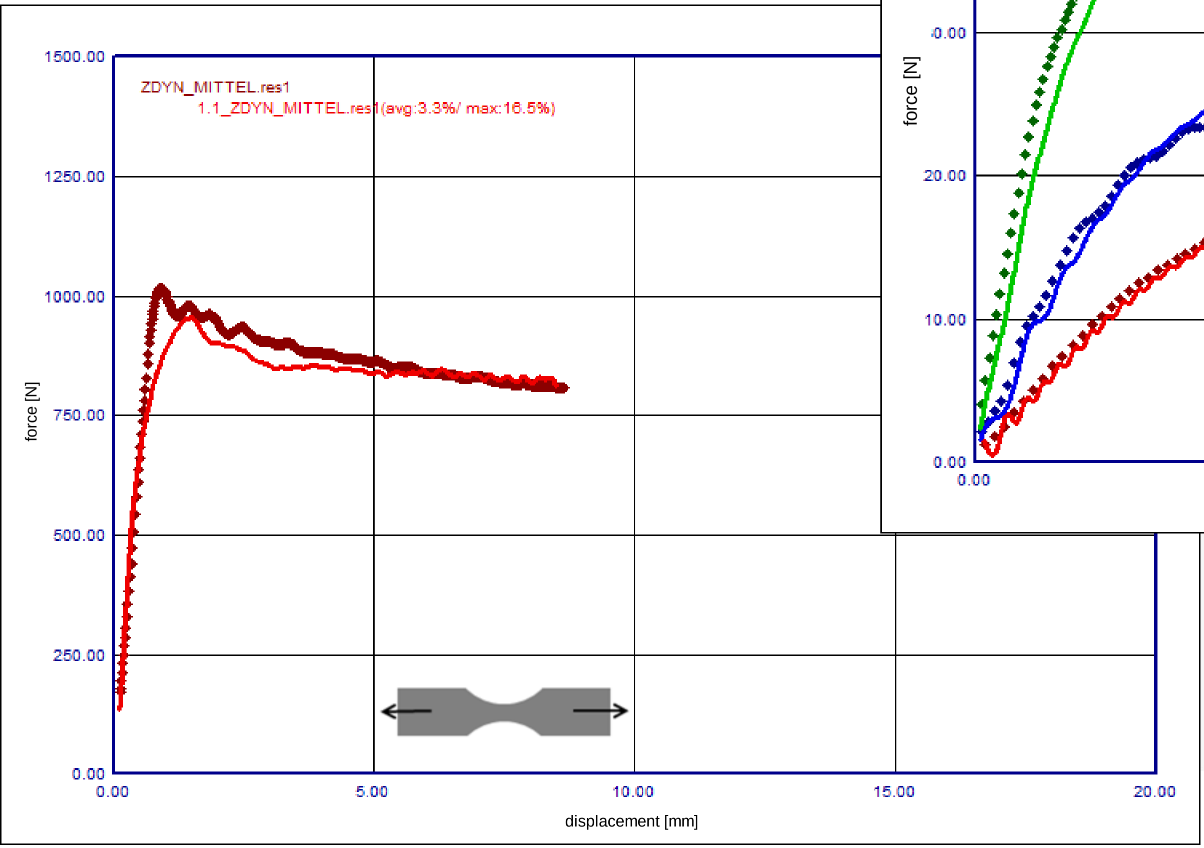
  or vice versa

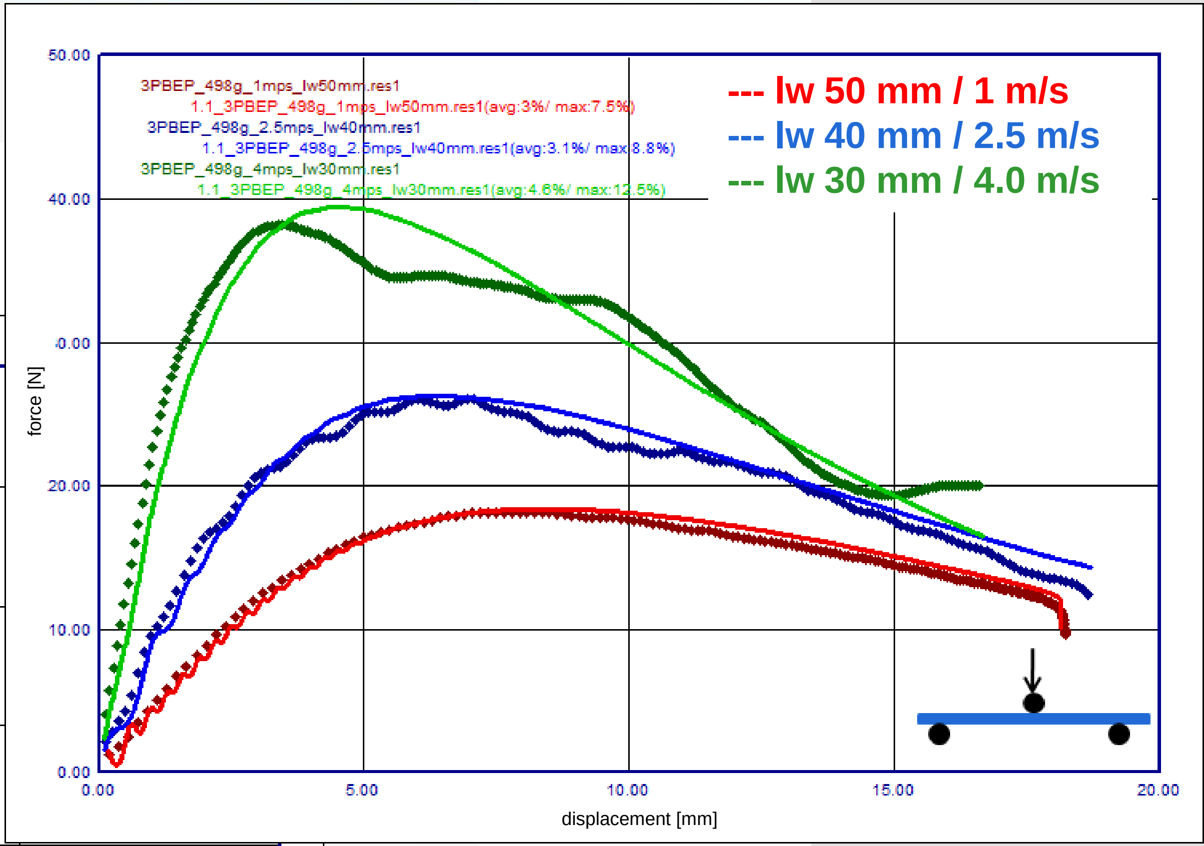


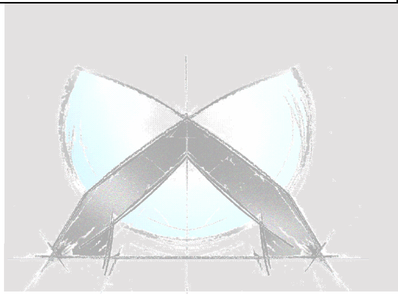


Generating material cards

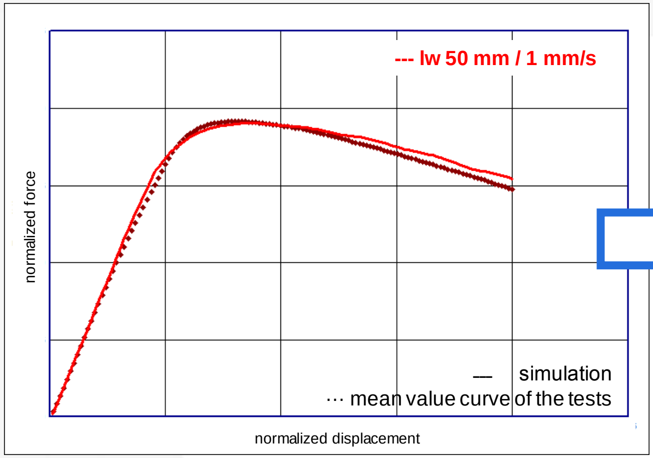
- LS-Dyna: *MAT187 (general yield surface)
- Tension/compression asymmetry
  → good conformity for all load cases



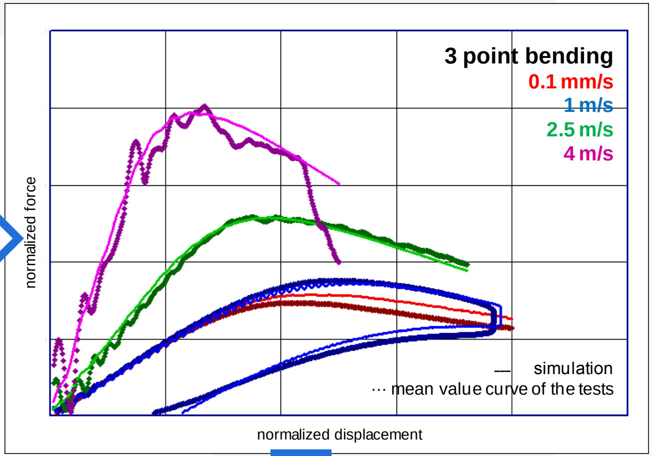




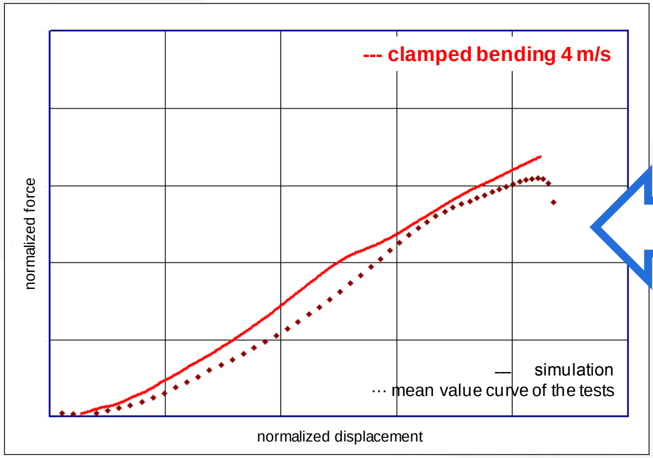
Reverse Engineering 4a impetus



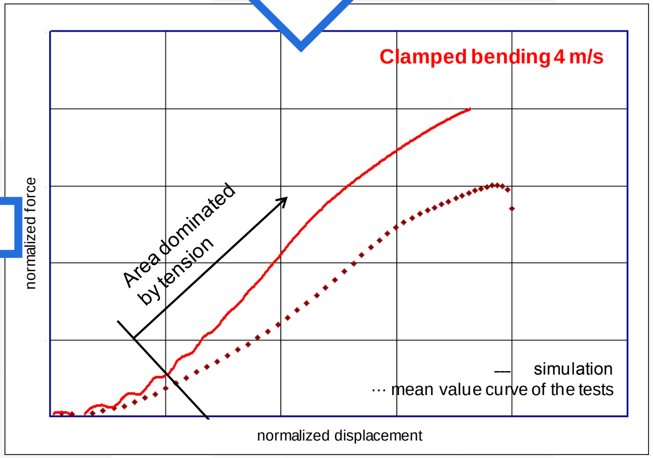
static behavior - yield



dynamic behavior – strain rate



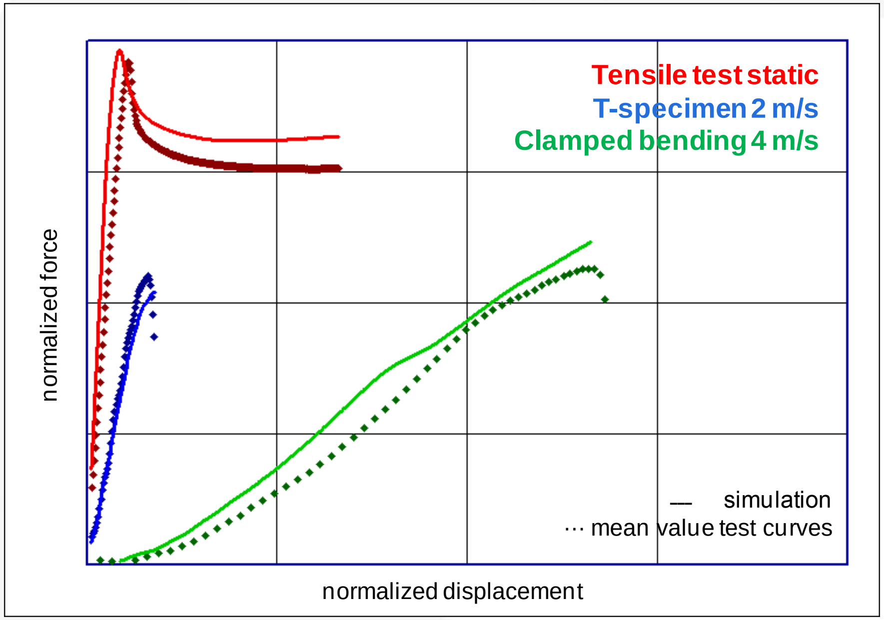
fit compression/tension behavior



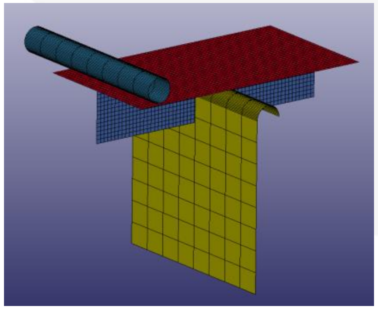
check compression/tension behavior

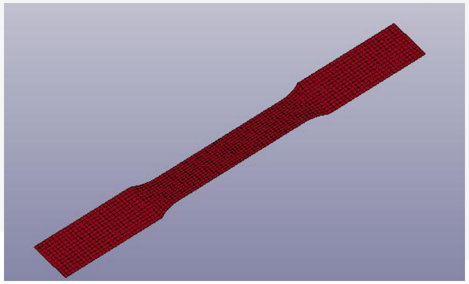
[5]

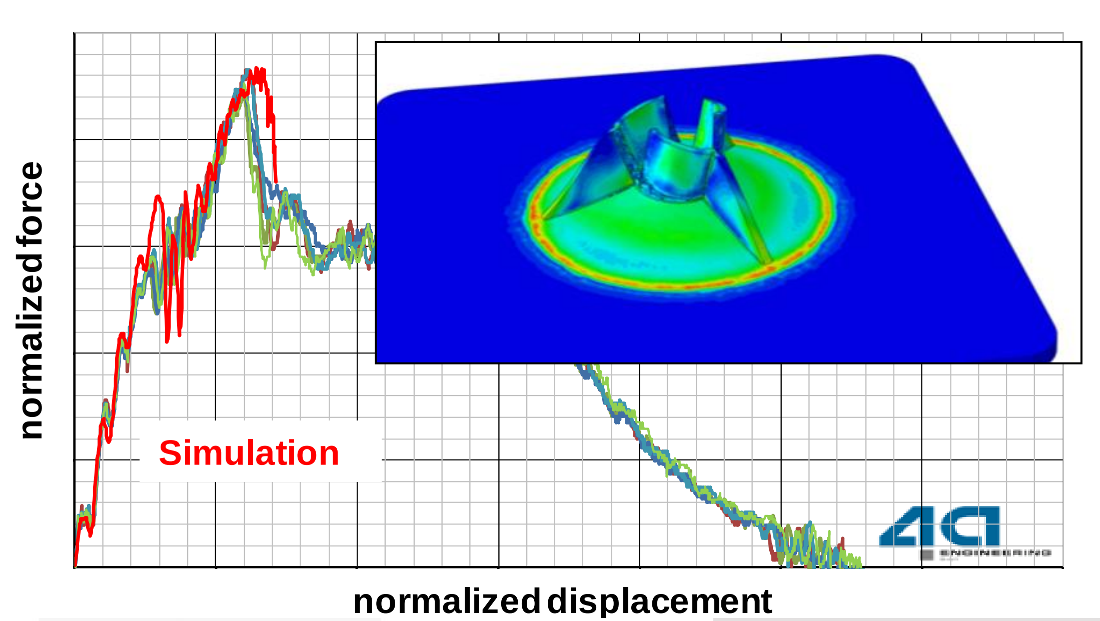
Validation 4a impetus (*MAT_SAMP-1)



dynamic T-specimen, static tension test



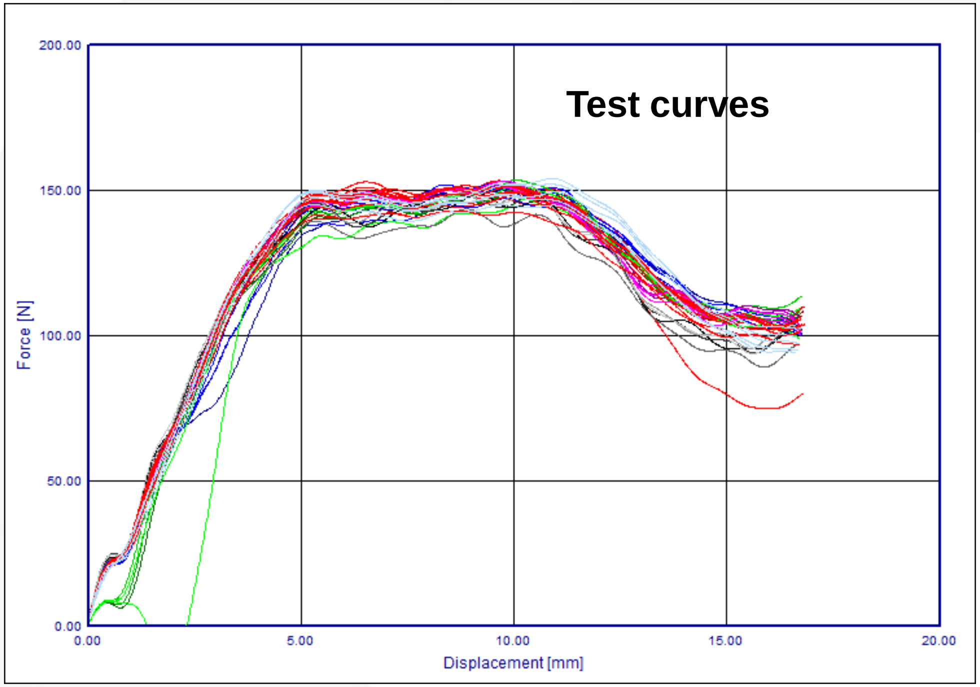


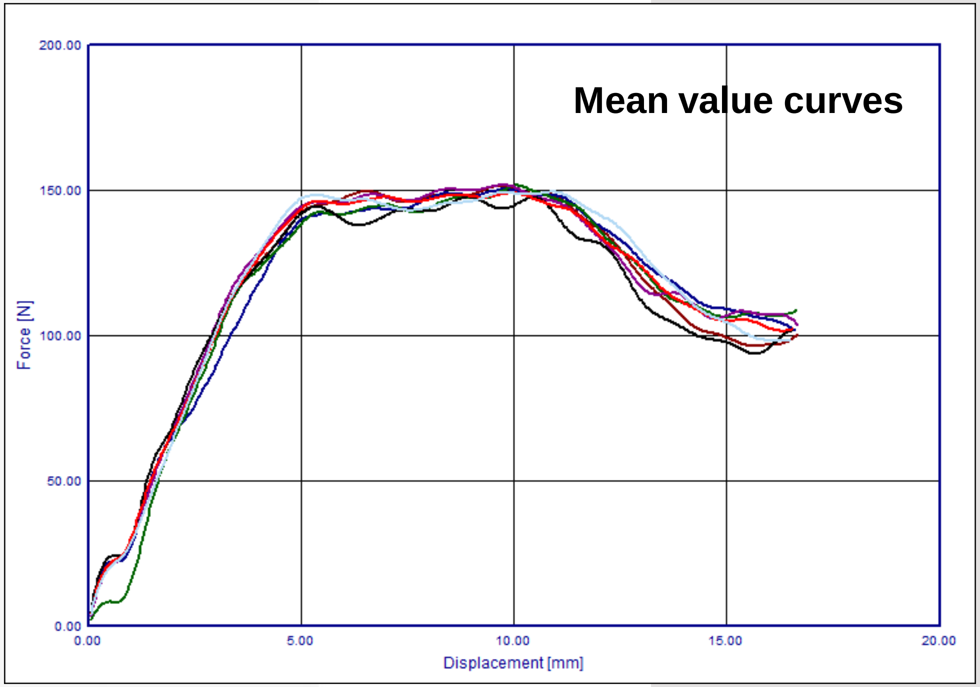


Dynamic puncture test with the part **[5]**
The test curves are matched very well

Examples of measurement results

Examples of measurement results
PCABS

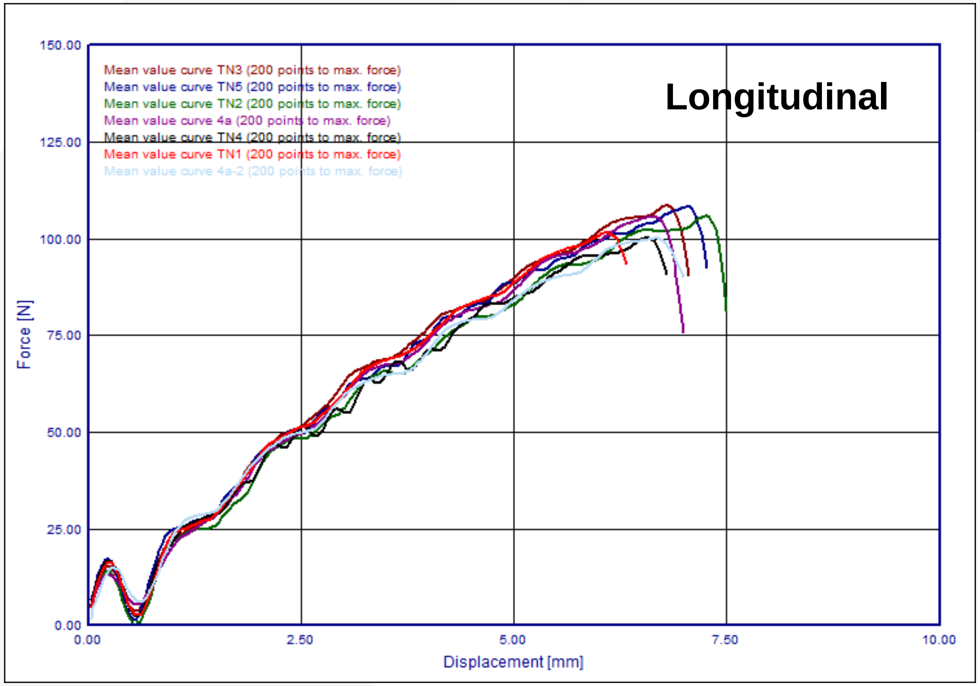


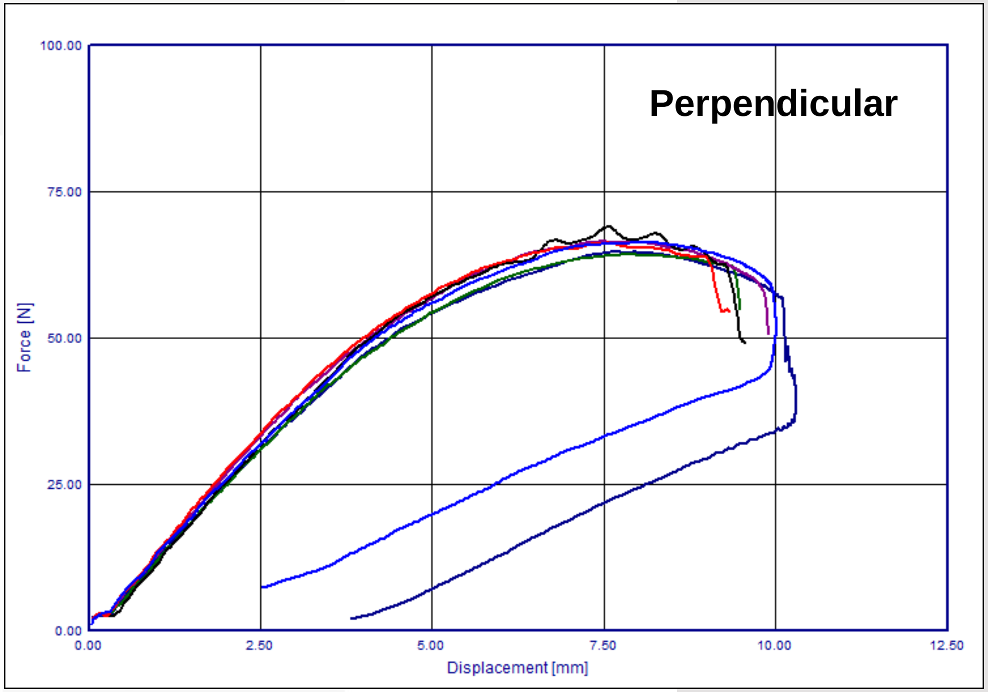


- Within a round robin test many materials were tested using the 4a impetus test systems of some customers.
- The results for the bending test of the material PCABS (thickness 3 mm) shows a good conformity for all 4a impetus test devices.

Examples of measurement results

PP GF30 longitudinal and perpendicular orientation

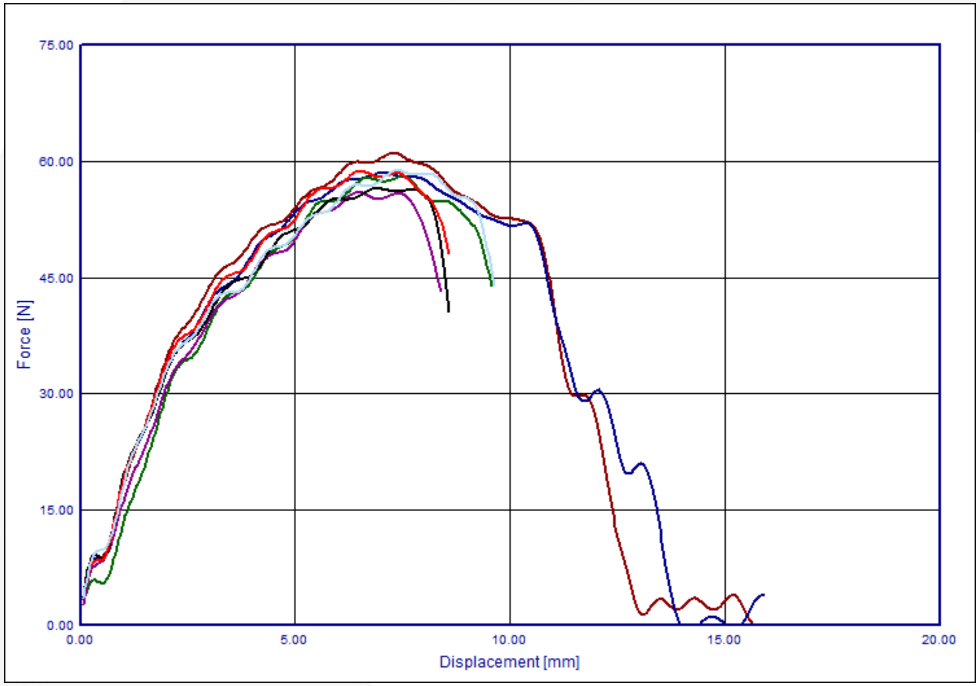


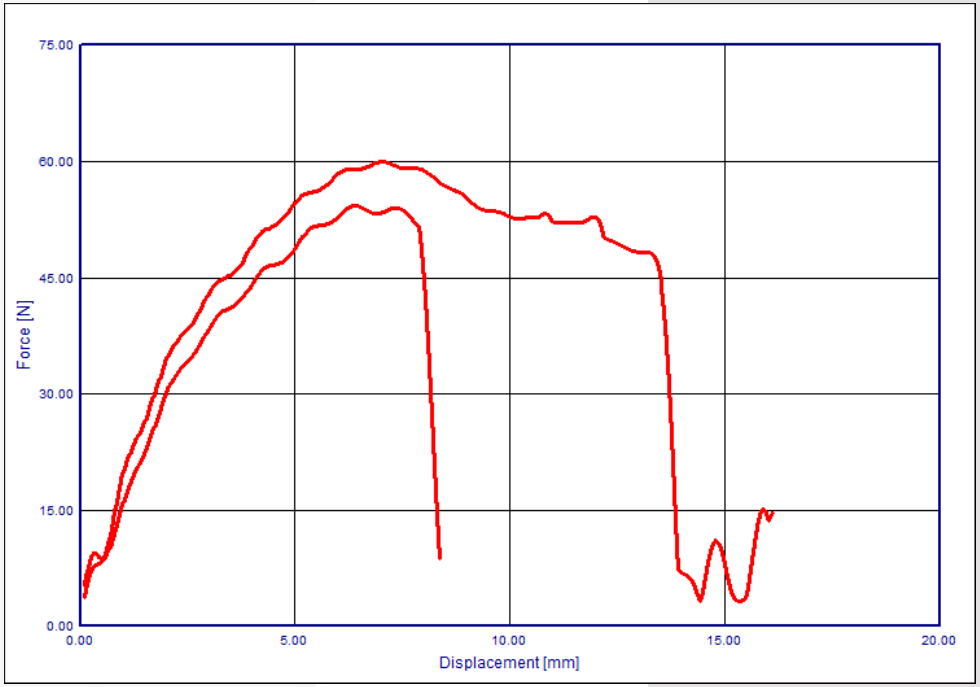


- The mean value curves of PP GF30 in longitudinal and perpendicular orientation are also well reproducible and comparable for all 4a impetus test systems.

Examples of measurement results

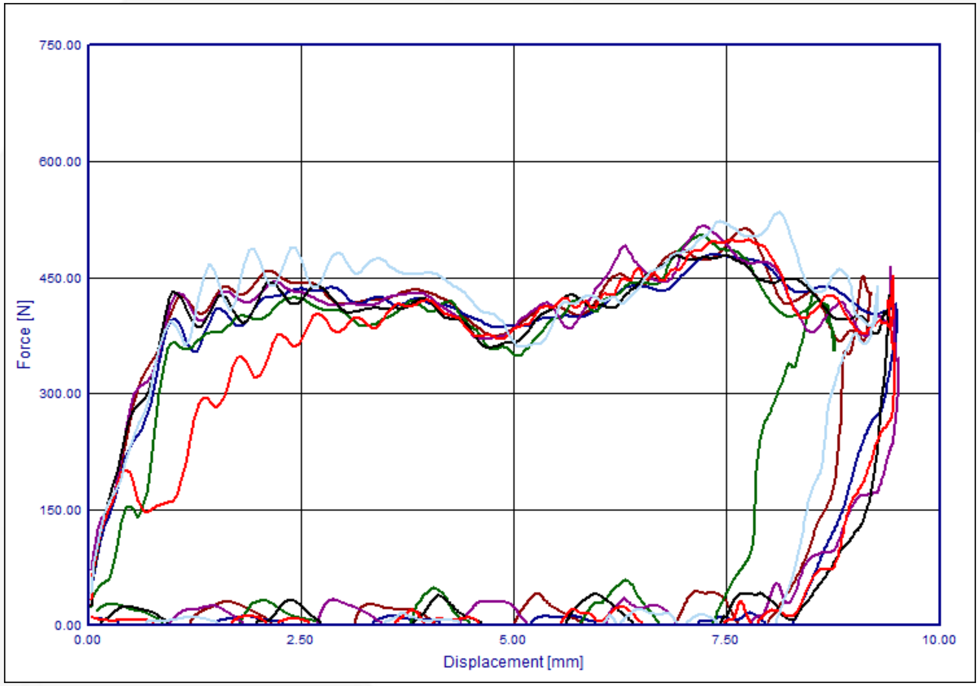
PPT20

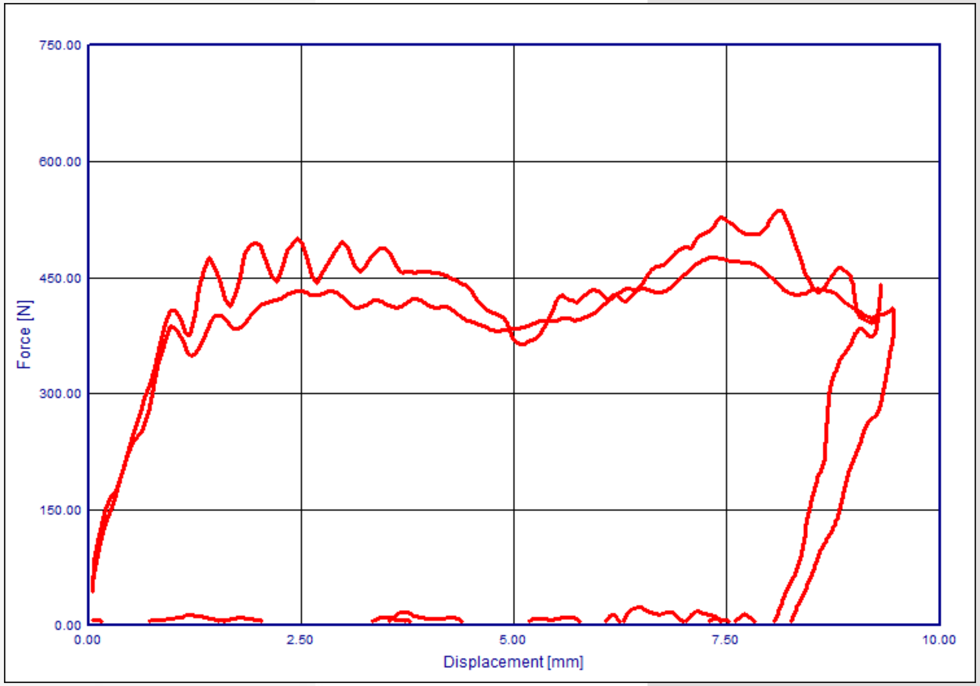




- The reinforced material PP T20 was tested on all 4a impetus test systems related to failure; the tests showed a well reproducibility.
- The range of failure is shown in the right diagram by the two extreme curves.

Examples of measurement results
Aluminum





- Using aluminum test specimens high forces and accelerations should occur. All 4a impetus test systems had a comparable result.
- The range of failure is shown again in the right diagram by the two extreme curves.

Further helpful links

- Homepage of 4a impetus: http://impetus.4a.co.at/en/
- Homepage of 4a engineering GmbH: http://www.4a-engineering.at/en/
- Homepage of the 4a technology day with many interesting presentations from various companies: http://technologietag.4a.co.at/
- Some recent papers about 4a impetus:

A. Fertschej, P. Reithofer, M. Rollant (4a engineering GmbH) - *Materialmodelle für Kunststoffe, Komplexe Fließflächen und Versagen*, 4a Technologietag 2014, Schladming (Link)

R. Jennrich, M. Roth, Prof. S. Kolling (Technische Hochschule Mittelhessen) C. Liebold (DYNAmore GmbH),G. Weber (Celanese GmbH) – *Experimentelle und numerische Untersuchung eines kurzglasfaserverstärkten Kunststoffes*, 13. LS-DYNA Forum 2014, Bamberg (Link)

P. Reithofer, B. Jilka (4a engineering GmbH), S. Hartmann, T. Erhart, A. Haufe (DYNAmore GmbH) – *Short and long fiber reinforced thermoplastics material models in LS-DYNA*, 13. LS-DYNA Forum 2014, Bamberg (Link)

A. Dietrich, M. Fritz, B. Jilka, P. Reithofer (4a engineering GmbH), B. Hofer, B. Fellner (MAGNA STEYR Fahrzeugtechnik AG & Co KG) - *Dynamische Material-charakterisierung von Composites mit 4a impetus*, 4a Technologietag 2013, Schladming (Link)

Summary

4a impetus

Summary

- 4a impetus offers comprehensive and fast testing possibilities
- Using reverse engineering appropriate material models are generated in an efficient way for the simulation (LS DYNA, PAM CRASH, ABAQUS, Radioss)
- Quasi-static tests can be integrated without any problem and effort.

- 4a impetus is an outstanding system to generate material data bases for everyday simulations.
- Quality control of the generated material cards is assured as 4a impetus is a complete software solution (testing and simulation) independent of the place of location.

Summary

- Unique test system
  - Double pendulum
  - Flexible pendulum (carbon arm, mass add, changeable sensors)
  - Instrumented (unique force–displacement)
- Unique software solution
  - Material characterization → material cards
- Markets
  - **Automotive**, aerospace, rail
  - Consumer goods (mobile phones, power tools, …)
  - Packing industries
  - Material supplier (plastics, composites, …)
  - Plastics manufacturing industries

Literature

[1] Mechanik der Kunststoffe

W. Retting, Hanser Verlag 1991

[2] Charaktersierung und Modellierung unverstärkter thermoplastischer Kunststoffe zur numerischen Simulation von Crashvorgängen

M. Junginger, Fraunhofer EMI Bericht 15/02

[3] Mechanical Characterization of Talc Particle Filled Thermoplastics

Frank Kunkel, Florian Becker, Stefan Kolling, Europäisches Dynaforum 2011, Straßburg

http://www.dynamore.de/de/download/papers/konferenz11/papers/session20-paper3.pdf

[4] Anpassung von Werkstoffmodellen für Polymere mittels dynamischer Pendelversuche

Anja Förderer, Dynamore Workshop Kunststoffe, Filderstadt, 2013

[5] Failure of Thermoplastics – Part 2 Material Modeling and Simulation

A. Fertschej, P. Reithofer, M. Rollant, Europäisches Dynaforum 2015, Würzburg